

**South Carolina Water Resources Research  
Institute  
Annual Technical Report  
FY 2008**

# Introduction

The South Carolina Water Resources Center uses its operating funds to carry out its mission as a liaison between the US Geological Survey, the university community and the water resources constituencies of those institutions. This is accomplished by serving as a water resources information outlet through our web site, by serving as a research facilitator through our annual grants competition and by operating as a catalyst for research and educational projects and programs across South Carolina. The Water Center also serves as a conduit for information necessary in the resource management decision-making arena as well as the water policy arena of the state.

The SCWRC recently completed a project funded through SC Sea Grant and called the “Development of a Conceptual Model for an Integrated Coastal Demographic-Economic-Environmental Prediction and Forecasting Initiative” (CIDEEP). That program provided coastal economic modeling through the Strom Thurmond Institute’s Regional Dynamics (REDYN) Input-Output (I/O) and Computable General Equilibrium (CGE) modeling engine program as well as additional land cover change modeling in collaboration with Towson University’s Geography Department.

The Institute, through its SC Water Resources Center developed and is expanding a nationally recognized urban growth model. Dr. Jeffery Allen heads the project. We have completed the coastal region of the state and most of the upstate. We continue to expand this activity as funding and time permits. Where completed we are using the model to assess competition for land between agriculture and forestry uses and residential growth. Model predictions for both regions of the state reveal significant losses of both agricultural and forest land covers to urban uses. These losses could significantly impact agriculture and forestry industries in South Carolina as well as numerous streams, rivers and lakes. We are currently developing an economic layer to the model to ascertain if residential pressures are simply pricing agriculture and forestry out of the market. In the Upstate we are using the model to assess water allocation during drought and to test the feasibility of creating a “water budget model” by which future developments water demands can be met. Drs. Allen and Michael Mikota direct the water budget program, supported by Drs. Caitlin Dyckman and Robert Becker. To compliment the water budget activity we have begun a project aimed at determining a monetary value for water. Support by the seven SC and GA counties surrounding Lake Hartwell, a project is under way to determine the economic impact of lake level fluctuations. The aim of the project is to develop a system of cap and trade models or tax credit models to develop optimal lake level management.

The Water Center continues to work on human population growth management issues as well as water quality and water quantity issues in the Saluda/Reedy watershed. The SCWRC completed work on the Upstate South Carolina urban growth prediction model. The results of the model have already been presented to numerous city and county councils as well as chamber’s of commerce. Numerous civic leaders have commented on the importance of the model in regard to both managing growth and development and protecting natural resources, especially receiving waters. Congressman Inglis’ office continues to work with the SCWRC to pursue funding for a water budget analysis for the Upstate based upon the results of the urban growth model.

SCWRC has recently funded studies to: 1) assess suspended sediment transport potential and supply in urbanizing coastal streams; and 2) the development of molecular genetic methods for detecting genes associated with the synthesis of microcystin-producing cyanobacteria. In addition, resources have been supplied to undertake a statewide assessment of water rates charged by water providers in order to determine more efficient pricing structures.

Meetings with key individuals from the South Carolina Department of Natural Resources, the South Carolina Department of Health and Environmental Control and South Carolina Sea Grant have produced a working group that will fund and undertake a multi-disciplinary research program for assessing management strategies

along the South Carolina coast. As an outcome of those meetings, the SCWRC has initiated work as a committee member of the SCDHEC-Ocean and Coastal Resource Management (OCRM) Shoreline Change Advisory Committee. That committee has been meeting regularly over eighteen months and will publish a report in late 2009 to SCDHEC-OCRM with recommendations and potential input into a new Beachfront Management Act for South Carolina. In addition, the SCWRC confirmed funding for a proposal to SCDHEC-OCRM on determining the state of the knowledge of shoreline retreat policies for coastal South Carolina.

Finally, the SCWRC initiated work on the Savannah River Basin with the U.S. Army Corps of Engineers and Duke Energy Corporation. The geographic area of the study initially consisted of all of the counties bordering Lake Hartwell. These counties include Anderson, Oconee, and Pickens in South Carolina and Franklin, Hart, and Stephens in Georgia. The study will focus on the 10 year time period from 1997 to 2007. The project will consist of two phases. Phase I will focus on the identification, collection, and analysis of quantitative data. Findings from this phase will help direct the research objectives of Phase II. The second phase will emphasize qualitative and quantitative data collection through interviews and surveys. Phase II will offer a combined study from information gathered in both phases. The synthesis from this knowledge will then be used to create a growth and development projection tool that will be able to forecast economic impacts based on varying lake levels. Emphasis will be placed on isolating lake level impacts while controlling for outside economic factors. Comparisons to other similar lakes with consistent data will be a measure that will provide a clearer assessment of the specific economic characteristics and dynamics attributed to Lake Hartwell. Duke Energy has funded a similar add-on project to nearby Lake Keowee and is interested in pursuing other projects throughout the Savannah River Basin.

## Research Program Introduction

The SCWRC finalized work for a project through SC Sea Grant and the “Development of a Conceptual Model for an Integrated Coastal Demographic-Economic-Environmental Prediction and Forecasting Initiative” (CIDEEP) program to provide coastal economic modeling through the Strom Thurmond Institute REDYN program as well as additional land cover change modeling in collaboration with Towson University’s Geography Department.

The Water Center has worked closely on human population growth management issues in the Saluda/Reedy watershed. The SCWRC completed work on the Upstate South Carolina urban growth prediction model. The results of the model have already been presented to numerous city and county councils as well as chamber’s of commerce. Numerous civic leaders have commented on the importance of the model in regard to both managing growth and development and protecting natural resources, especially receiving waters.

SCWRC has funded studies to: 1) build a statewide biomarker approach to investigate pollution effects on fish in wadeable streams of South Carolina; and 2) build a statewide sediment and water quality approach to characterize pollution in wadeable streams of South Carolina. In addition, resources have been supplied to undertake a statewide assessment of water rates charged by water providers in order to determine more efficient pricing structures.

The SCWRC finished a report to SCDHEC-OCRM on determining the state of the knowledge of shoreline retreat policies for coastal South Carolina. The report that follows provides findings of a parallel study commissioned by the Office of Ocean and Coastal Resource Management of the South Carolina Department of Health and Environmental Control. The study has three parts that include:

1. an examination of historical, current and emerging trends in shoreline management in coastal states in the US,
2. an assessment of the effectiveness of beachfront management in reducing losses along the South Carolina shoreline, and
3. a compilation of stakeholder input to identify key issues and options for addressing long-term shoreline change in the state in South Carolina.

SCWRC has recently funded studies to: 1) assess suspended sediment transport potential and supply in urbanizing coastal streams (PI: Dr. Anand Jayakaran); and 2) the development of molecular genetic methods for detecting genes associated with the synthesis of microcystin-producing cyanobacteria (PI: Dr. Alan Johnson). In addition, resources have been supplied to undertake a statewide assessment of water rates charged by water providers in order to determine more efficient pricing structures.

# A Statewide Biomarker Approach to Investigate Pollution Effects on Sunfish (Lepomis sp.) in Wadeable Streams of South Carolina

## Basic Information

|                                 |  |
|---------------------------------|--|
| <b>Title:</b>                   | A Statewide Biomarker Approach to Investigate Pollution Effects on Sunfish (Lepomis sp.) in Wadeable Streams of South Carolina |
| <b>Project Number:</b>          | 2007SC49B  |
| <b>Start Date:</b>              | 3/1/2007   |
| <b>End Date:</b>                | 2/28/2009  |
| <b>Funding Source:</b>          | 104B   |
| <b>Congressional District:</b>  | Third  |
| <b>Research Category:</b>       | Not Applicable   |
| <b>Focus Category:</b>          | Water Quality, Toxic Substances, Surface Water   |
| <b>Descriptors:</b>             | Conservation, Environmental Risk Assessment, Biomarkers, Fish Toxicology, Point Sources, Non-point Sources                     |
| <b>Principal Investigators:</b> | Peter Van Den Hurk, Stephen Klaine, Marc C. Scott  |

## Publication

# **Progress Report**

**July 2008**

## **A Statewide Biomarker Approach to Investigate Pollution Effects on Sunfish (*Lepomis* sp.) in Wadeable Streams of South Carolina.**

**Peter van den Hurk<sup>1</sup>, Andrew Sayer<sup>1</sup>, Stephen J. Klaine<sup>1</sup>, Marc C. Scott<sup>2</sup>**

**Sponsored by:**

**SOUTH CAROLINA WATER RESOURCES CENTER**

**SOUTH CAROLINA COMPETITIVE GRANTS PROGRAM**

<sup>1</sup> Department of Biological Sciences, Institute of Environmental Toxicology, Clemson University, 237 Long Hall, Clemson, SC 29634 <sup>2</sup> South Carolina Department of Natural Resources

## Executive summary

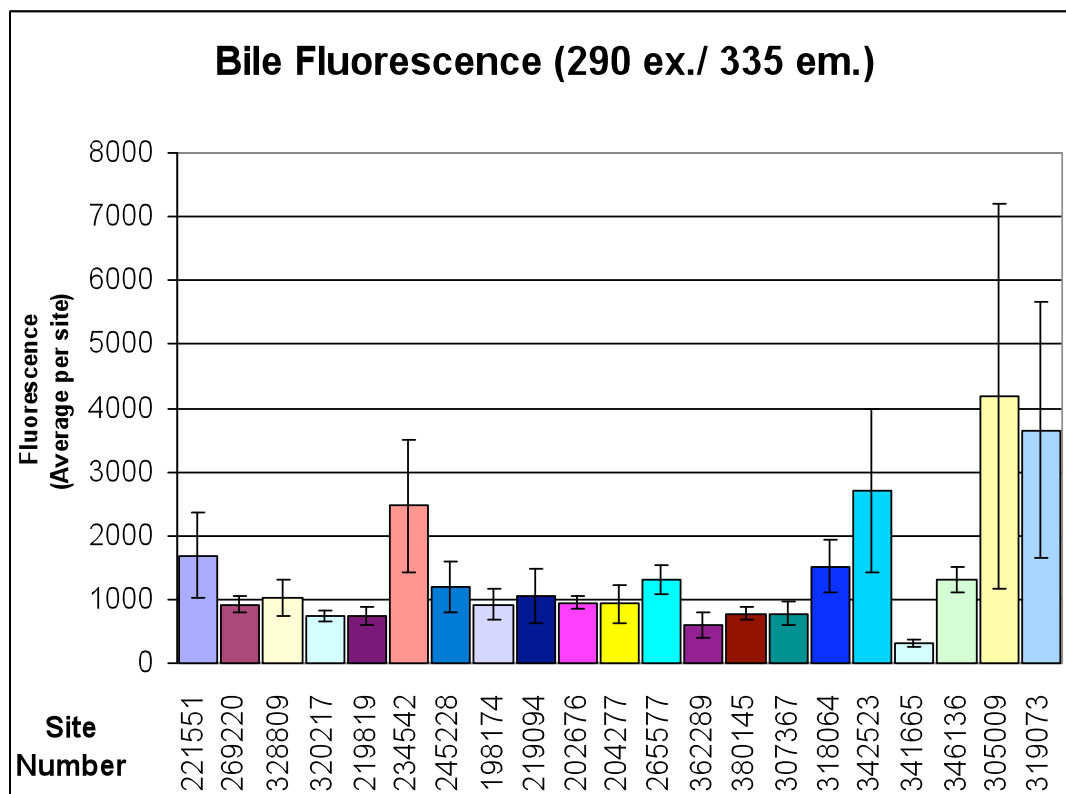
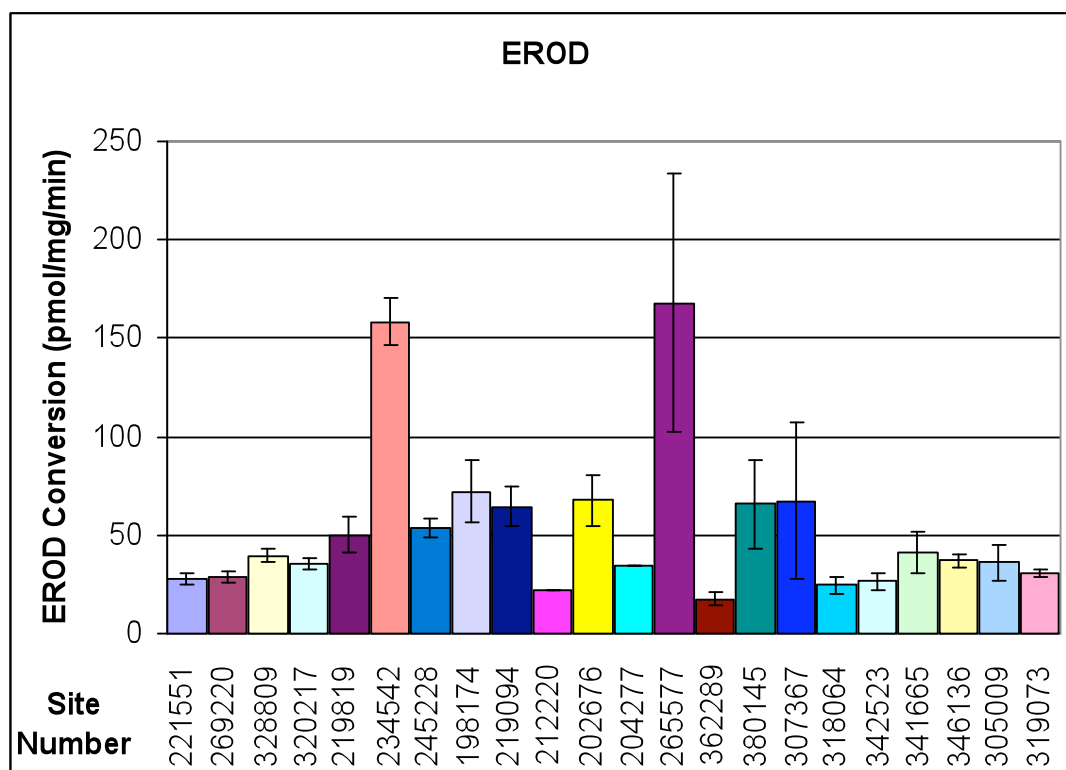
The numbers of freshwater species in South Carolina have been under pressure for many years. However, the threats that these organisms face from point and non-point source pollution is largely unknown. In May 2006 the South Carolina Department of Natural Resources (SCDNR) began a five year survey to establish the species richness and abundance of fish species in the wadeable streams of South Carolina. In addition to the fish population parameters, one of the goals of this study is to use molecular biomarkers of contaminant exposure to assess the health of fish populations in South Carolina's freshwater streams. Another objective of the project is to correlate the biomarker responses with fish population parameters and with land use data from the sampled watersheds.

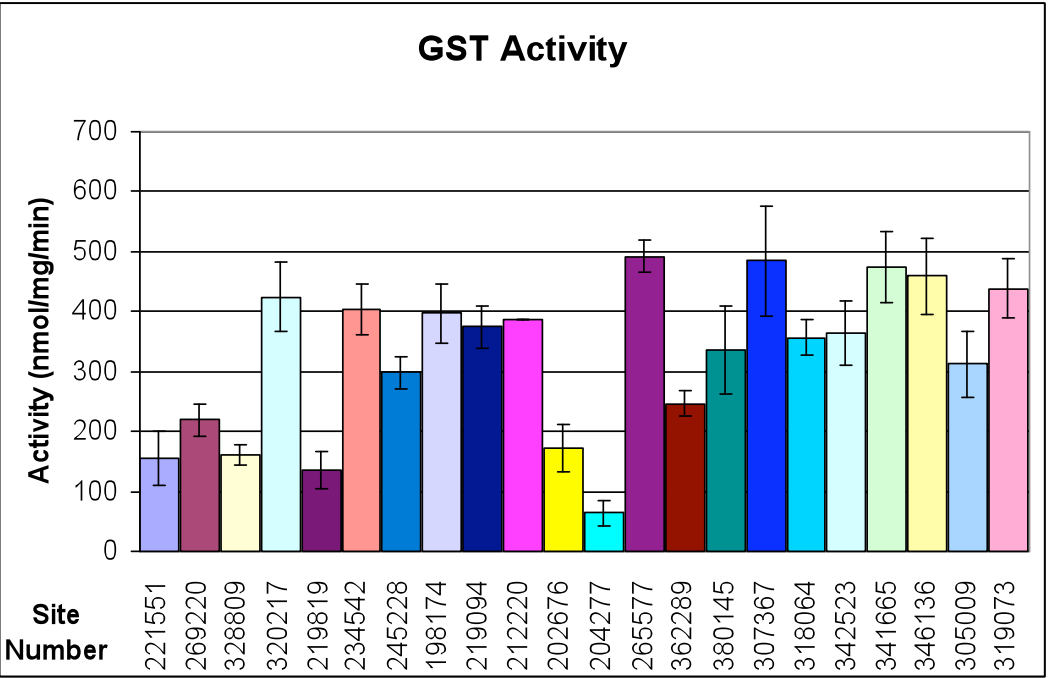
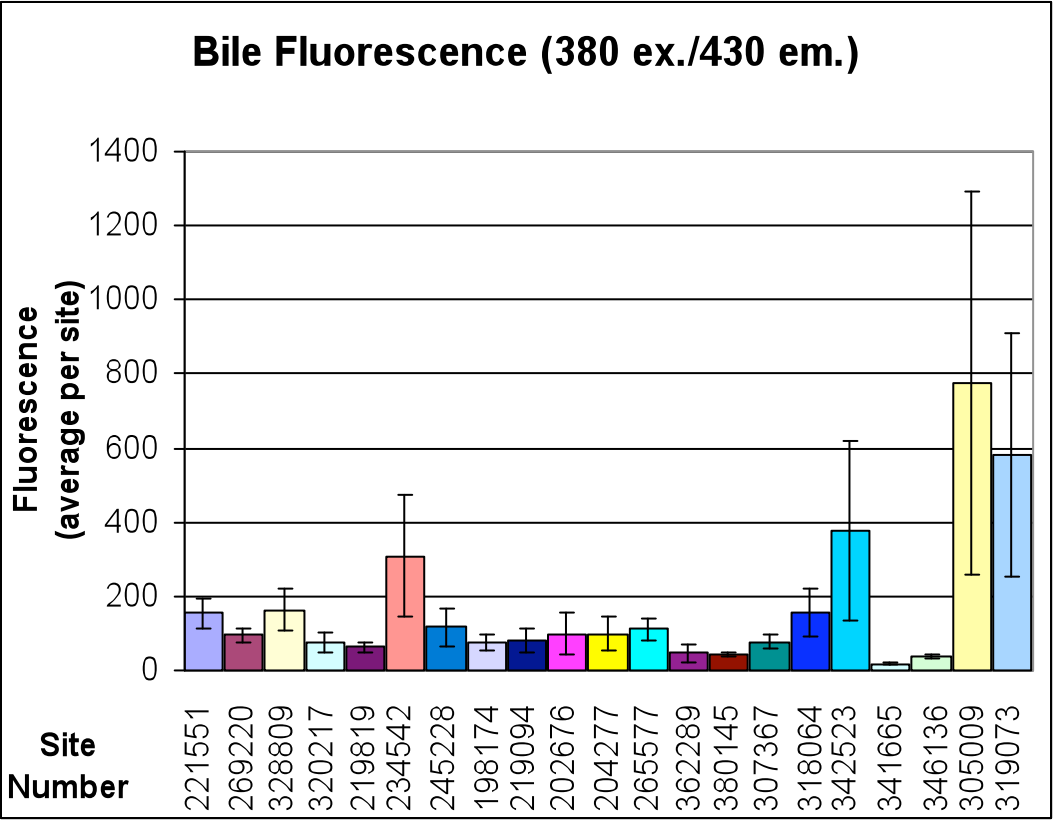
During the second year of the study, different sunfish species (*Lepomis* sp.) were collected from May through September 2007 at 22 randomly selected sites in the Mid-Atlantic Coastal Plain watersheds in South Carolina. Somatic indices, including hepatosomatic index (HSI), spleen somatic index (SSI), gonadosomatic index (GSI) were measured to determine the overall physiological condition of the fish. Cytochrome p4501A (CYP1A) induction (as measured by the EROD assay) and bile fluorescence based on 2-ring, 4-ring and 5-ringed compounds were measured to estimate exposure to polycyclic aromatic hydrocarbons (PAHs). Glutathione S-transferase (GST) was measured to estimate oxidative stress, and the estrogen receptor binding assay was used on bile samples to measure exposure to endocrine disrupting compounds.

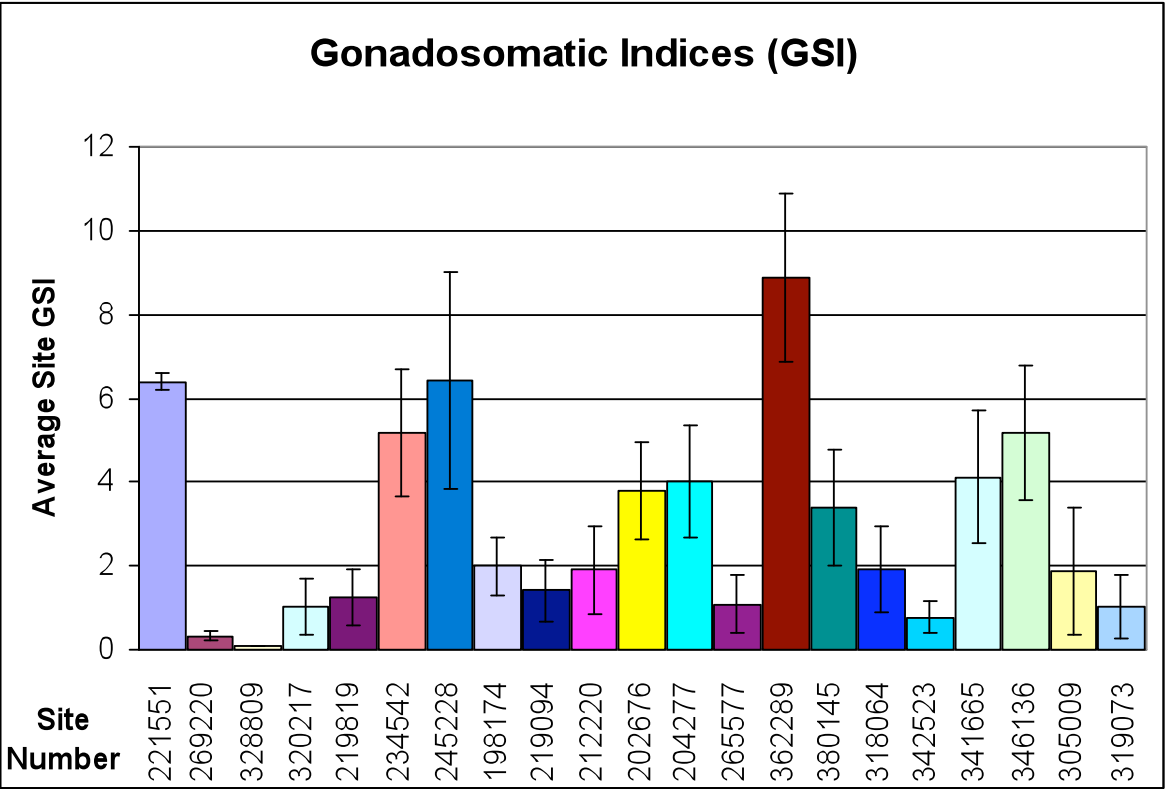
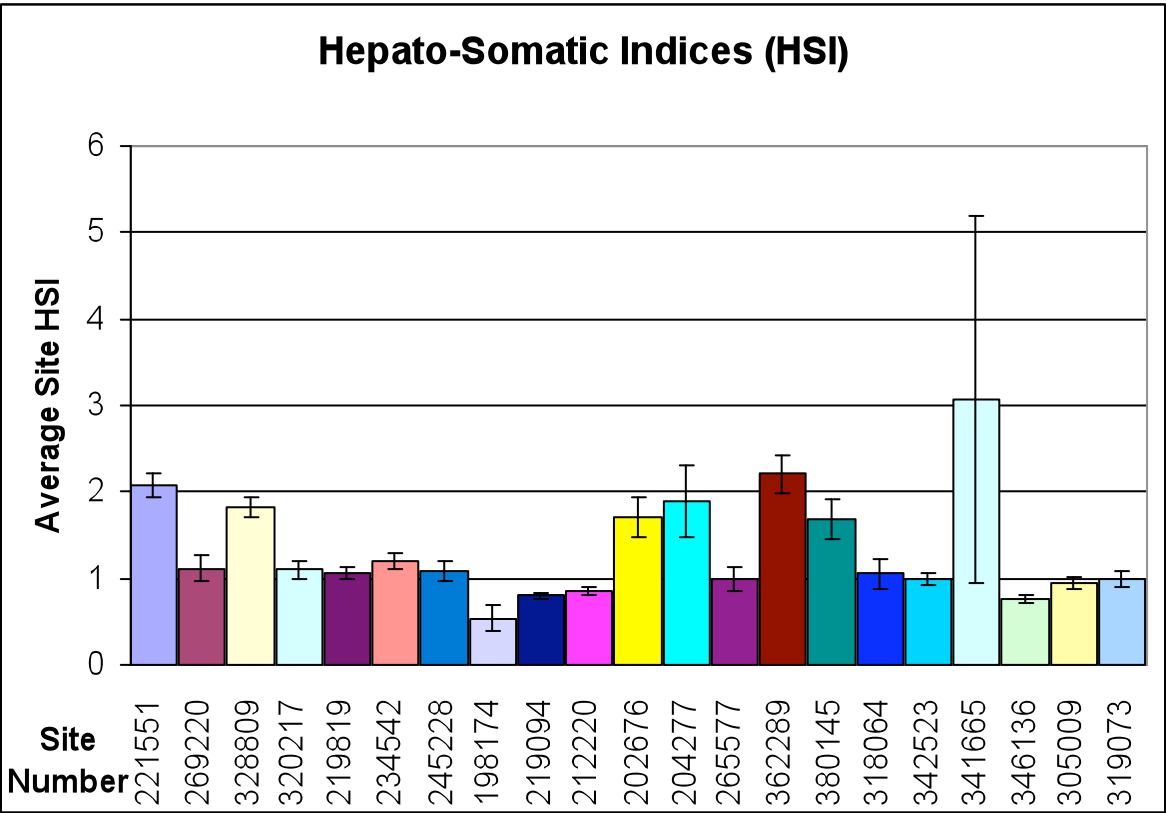
The first results showed that there was a variety of responses among the sample sites investigated. The EROD assay demonstrated that there were at least two sites where fish had been exposed to CYP1A inducing compounds. For one site, this induction coincided with increased bile fluorescence, indicating that PAHs were present at the site, and were able to trigger a biomarker response. At the other sites, the bile did not have an increased fluorescence, which excludes PAHs as inducing agents. Other CYP1A inducers were probably present at this site, or the CYP1A induction is a demonstration of a previous, temporary PAH exposure. Several sites showed increased bile fluorescence in some individuals, but this exposure did not yet lead to CYP1A induction. GST activity was induced in a large number of sites. It is unclear if there was actually exposure to compounds that can be responsible for this induction, or if there was suppression of GST activity at the sites that had lower activity than average.

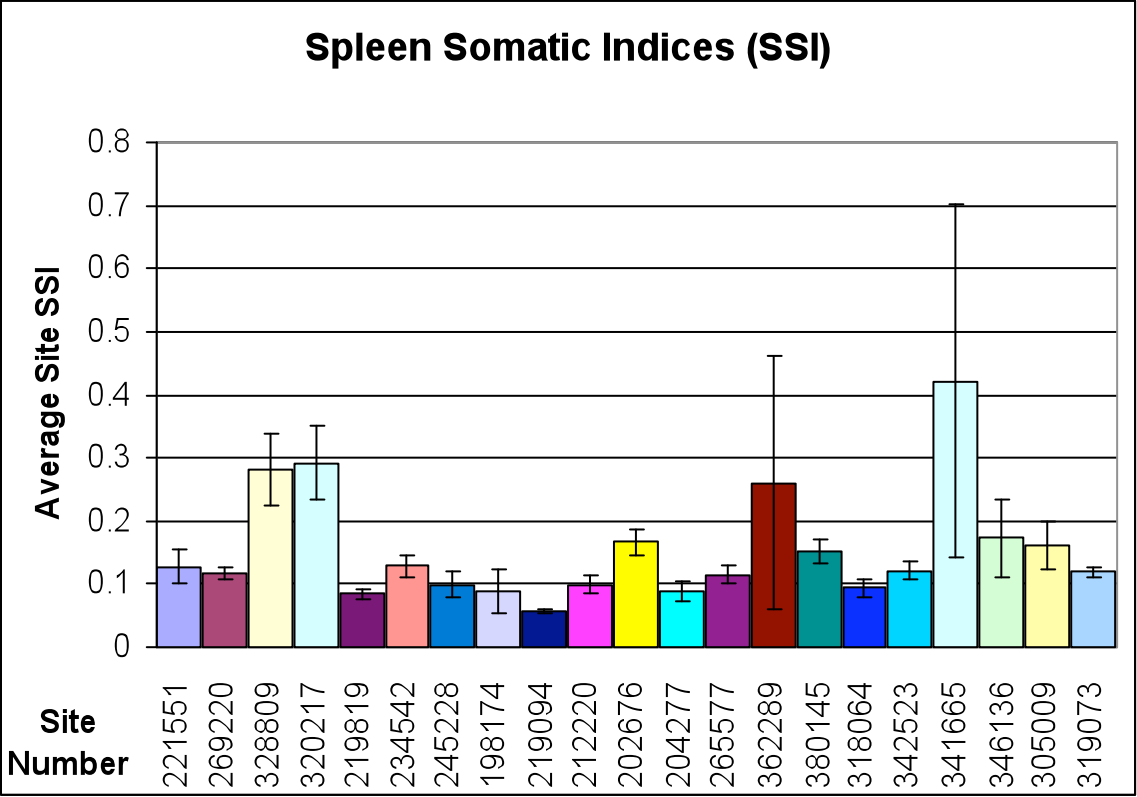
The somatic indices showed a varied response picture. Previous investigations have suggested that an increased spleen weight may be related to increased parasite loadings. At this point we can not draw a conclusion about this because spleen or liver histology is not available. The gonado-somatic index also showed a diverse pattern, but results from the previous year suggest that this is related to time in the season that the fish were collected.

In conclusion we can say that most sites in the sample area were close to pristine, with very few sites that were under anthropogenic influence. In further analysis of the data we will compare these biomarker and fish health parameters with land use parameters and water chemistry data.









# A Statewide Sediment and Water Quality Approach to Characterize Pollution in Wadeable Streams of South Carolina (Phase 2).

## Basic Information

|                                 |  |
|---------------------------------|--|
| <b>Title:</b>                   | A Statewide Sediment and Water Quality Approach to Characterize Pollution in Wadeable Streams of South Carolina (Phase 2). |
| <b>Project Number:</b>          | 2007SC50B  |
| <b>Start Date:</b>              | 3/1/2007   |
| <b>End Date:</b>                | 2/28/2009  |
| <b>Funding Source:</b>          | 104B   |
| <b>Congressional District:</b>  | Third  |
| <b>Research Category:</b>       | Not Applicable   |
| <b>Focus Category:</b>          | Water Quality, Sediments, Surface Water  |
| <b>Descriptors:</b>             |  |
| <b>Principal Investigators:</b> | Elizabeth R. Carraway, Stephen Klaine, Marc C. Scott   |

## Publication

Report for the South Carolina Water Resources Center, Clemson University

A Statewide Sediment and Water Quality Approach to Characterize  
Pollution in Wadeable Streams of South Carolina

prepared by Elizabeth R. Carraway and Alan J. Jones

Project information

Principal Investigator: Elizabeth R. Carraway, Clemson University, Environmental Engineering and Earth Sciences and Clemson Institute of Environmental Toxicology, 342 Computer Ct., Anderson, SC 29625, 864-656-5574, [ecarraw@clemson.edu](mailto:ecarraw@clemson.edu)

Co-investigators:

Stephen J. Klaine, Ph.D., Professor, Clemson University, Department of Biological Sciences and Clemson Institute of Environmental Toxicology, 509 Westinghouse Rd., Pendleton, SC 29670, 864-646-2188, [sklaine@clemson.edu](mailto:sklaine@clemson.edu)

Mark C. Scott, Ph.D., Research Biologist, South Carolina Department of Natural Resources, 153 Hopewell Rd., Pendleton, SC 29670, 864-654-6346 ext. 14, [scottm@dnr.sc.gov](mailto:scottm@dnr.sc.gov)

**ABSTRACT**

The South Carolina Department of Natural Resources (SCDNR) began in 2006 a statewide effort to “conduct an assessment of wadeable streams to gather appropriate data that will allow SCDNR to design effective and efficient management strategies to protect, conserve, and restore the aquatic resources of the State.” In collaboration with SCDNR and other Clemson University researchers, water and sediment samples have been collected from 98 sites in 2006 and 2007. These samples have been analyzed for 19 metals using ICP-MS and ICP-AES. Six metals (chromium, copper, lead, nickel, silver and zinc) were found to exceed USEPA values for Constant Contaminant Concentration (CCC) and Contaminant Maximum Concentration (CMC), however, only copper (39 sites) and lead (30 sites) were found in excess at a large number of sites. Literature reported threshold effects concentrations (TEC) and probable effects concentrations (PEC) for arsenic, cadmium, chromium, copper, lead, nickel, and zinc were used to assess potential risk of sediment ecotoxicity. TEC levels were exceeded for all of the metals at two to eight sites each, with the notable exception of lead which exceeded the TEC at all sites except two. No sites exceeded a PEC. Correlation of metal concentrations with land use show most significant concentrations for dissolved nutrient metals (potassium, magnesium) and a few trace metals (notably chromium, nickel, and lead) with agriculture in a 100m strip around the streams as well as with forests in that strip. Correlations with full watershed land use are fewer and weaker. Sediment silver concentrations were also found to correlate with land development activities. Initial results from Principal Components Analysis (PCA) for the entire data set indicate a relationship of dissolved nutrient metals with development and forest land uses in the full watersheds.

## INTRODUCTION

Freshwater species worldwide face accelerated extinction rates relative to most other wildlife taxa. The southeastern US in particular has been suffering long-term declines in native species of fish and aquatic invertebrates. The Comprehensive Wildlife Conservation Plan (CWCP) submitted to the US Fish and Wildlife Service by the SC Department of Natural Resources (SCDNR) in 2006 describes priority species of concern, including over 125 species of fish, herpetofauna, mussels, crayfish, and snails that are directly dependent on aquatic systems. Common threats to these species are linked to point and non-point source pollution. Water coursing through freshwater streams integrates effects in the entire drainage area, with consequences of land use ending up in rivers, reservoirs, and coastal systems.

SCDNR, aided by funding from US Fish and Wildlife, began in 2006 a multi-year characterization of fish populations in three hundred wadeable streams across the State. These small watersheds are characteristic of larger “ecobasins” or designations of unique combinations of river basin drainage and ecoregion. Fish and invertebrate samples support characterization of population densities and aquatic community structure and development of indices of ecosystem health. SCDNR personnel and Clemson University researchers have been collaborating to maximize the value of this multi-year endeavor by adding characterization of chemical pollution and fish biomarker responses at the sampling sites.

The characterization of metal and organic chemical pollutants in water and sediment samples has been the focus of this project, funded by the South Carolina Water Resources Center. Results for metals (except mercury) in samples collected in 2006 and 2007 are presented in this report. For organic pollutants in water and for mercury in water and sediments, the following summary is given. The results obtained for the laboratory “tracer” organic compound have been good.

Meclofenamic acid was added to each water sample just before processing (extraction, derivatization, instrumental analysis) in the laboratory. This compound is similar to compounds of interest, but degrades rapidly under normal environmental conditions. Thus, it is expected to be present below detection limits and, when spiked into samples, to test analyst technique and instrument performance. The derivatized meclofenamic acid is observed in GC/MS chromatograms at the concentrations expected, indicating good recovery and detection. Quantitation of 17 $\alpha$ -ethynylestradiol, 4-nonylphenol, caffeine, triclosan, atrazine, pyrene, benzo(a)pyrene, phenanthrene, and anthracene in water samples has showed results generally below detection limits except at one site where caffeine was found. Samples from several sites show responses similar to mixtures derived from diesel fuels or biological activity (e.g., fatty acids). Measurements of dissolved mercury have been below detection limits (15 ppt) but sediment-associated mercury levels are detectable.

## **MATERIALS AND METHODS**

*Site Selection.* The generation of sampling sites at random locations in wadeable streams was conducted by SCDNR. A Geographical Information Systems (GIS) method was used to delineate stream locations with watershed areas less than 150 km<sup>2</sup>. Potential sites were scouted by SCDNR to determine sampling suitability and to make changes necessary to avoid obstructions and excessively wide or deep stream sites.

*Sampling Methods.* For all sampling and analysis techniques a series of quality control blanks, spiked blanks, replicates and spiked samples were measured. All sample bottles were acid-washed and rinsed twice with 18m $\Omega$ •cm water. Total metals samples were collected (2007 only) in pre-cleaned, acid washed 250 ml brown high-density polyethylene bottles (Nalgene); 3 ml of trace metal grade nitric acid was added (Mallinckrodt Chemicals). Dissolved metals samples

were filtered onsite with 47 mm Supor filters (Pall Life Sciences) into pre-cleaned, acid washed 250 ml brown high-density polyethylene bottles. The homemade filtering device consists of a pressurizable garden sprayer fitted with a 47 mm inline polystyrene filter holder (Fisher Scientific) with polyethylene tubing. The apparatus was cleaned between each sample with DI water and rinsed twice with new site water. It was acid washed after each sampling trip (roughly 5 to 6 samples). Mercury samples were collected in the same manner, but with 125 ml brown borosilicate glass bottles with a PTFE lined cap. Sediments were collected as “scoop” samples in 50 ml conical vials and acidified. All samples were stored in the dark on ice for no more than 72 hours before returning to the lab.

*Sample Preparation and Analysis.* Filtered aqueous samples did not require further treatment. Total aqueous metals samples were digested using US Environmental Protection Agency (USEPA) Method 3015a (Microwave Assisted Acid Digestion of Aqueous Samples and Extracts). A 45 ml sample aliquot was acidified with 4 ml trace metal grade nitric acid and 1 ml trace metal grade hydrochloric acid. The mixture was transferred to a microwave digestion vessel (Milestone and CEM models were used), heated to  $170\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$  in ~10 minutes, and held at  $170\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$  for 10 minutes. Cooled samples were transferred to 50 ml HDPE vials for storage at  $4\text{ }^{\circ}\text{C}$  until analysis. Digestion vessels were cleaned with the same acids and temperature program between each run.

Sediment metals were digested using USEPA Method 3051a (Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils). Approximately 0.5 g dried (at  $60^{\circ}\text{C}$ ) sample was combined with 9 ml trace metal grade nitric acid and 3 ml trace metal grade hydrochloric acid, transferred to a digestion vessel, heated to  $175^{\circ}\text{C} \pm 5^{\circ}\text{C}$ , and held at that temperature 5 minutes. Cooled samples were transferred to a 50 ml volumetric flask, diluted to 50.00 ml, and

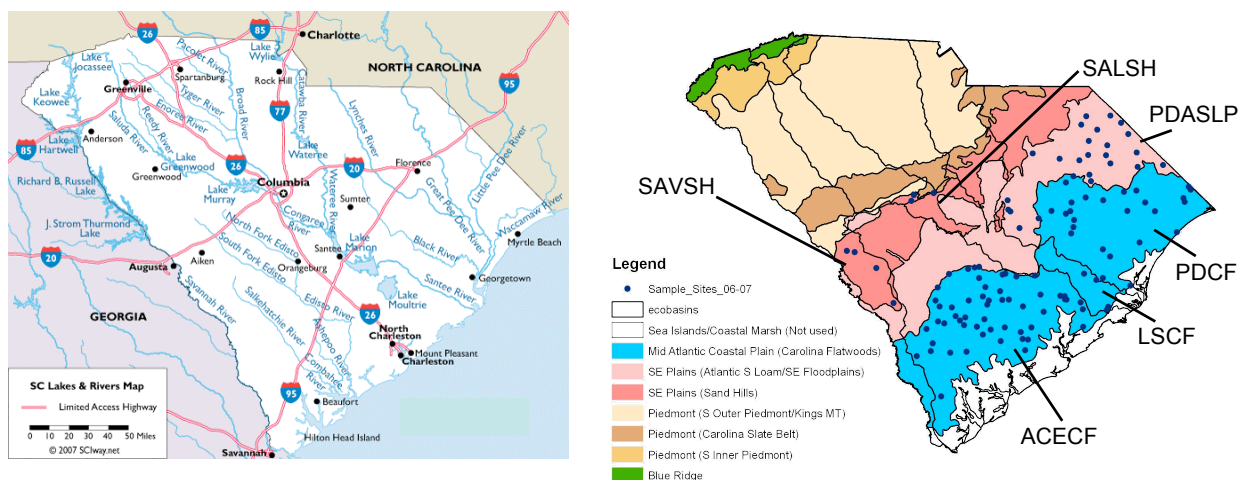
transferred to a 50 ml HDPE conical vial. Samples were centrifuged 20 minutes at 500 G, decanted, and analyzed. Vessels were cleaned with the same acids and digestion program.

Filtered and digested samples were analyzed using ICP-MS and ICP-AES. The Laboratory for Environmental Analysis at the University of Georgia (<http://www.uga.edu/lea/>) performed ICP-MS analysis for the following ten metals: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), selenium (Se), silver (Ag), thallium (Tl), and zinc (Zn). The Agricultural Services Laboratory at Clemson University (<http://www.clemson.edu/agsrvlb>) performed ICP-AES analysis for the following twelve elements: aluminum (Al), boron (B), calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P), potassium (K), sodium (Na), sulfur (S), and zinc (Zn). Thus the samples were analyzed for nineteen metals plus sulfur. The analysis of copper and zinc by both laboratories is an added quality control.

*Land Use Comparisons and Statistical Analysis.* Land use data provided by SCDNR were correlated with metals concentrations using linear regression. Principle Components Analysis was also performed.

## **RESULTS AND DISCUSSION**

Figure 1 part A indicates major rivers in SC and part B major ecobasins and ecoregions. Upstate to low country lines show river basins and their overlap with ecoregion classes (e.g., pink plains, brown piedmonts) delineate ecobasins. The points indicate sampling sites (successful and unsuccessful, dry attempts); ecobasin abbreviations are explained in Table 1. The table also indicates the number of sites from which samples (water and sediment) were obtained in each ecobasin. Appendix A contains site abbreviations used in this report and sampling dates.



**Figure 1. SC rivers, ecoregions, ecobasins, and 2006-2007 sampling sites**

A. Major SC lakes and rivers ([www.sciway.net/maps/south-carolina-lakes-rivers.html](http://www.sciway.net/maps/south-carolina-lakes-rivers.html))

B. 2006-2007 sampling sites (including dry sites), ecobasins, and ecoregions.

**Table 1. Ecobasin abbreviations, descriptions, and samples obtained**

| <i>Ecobasin abbreviation</i> | <i>River basin</i>                 | <i>Ecoregion</i>                        | <i># Samples (2006-2007)</i> |
|------------------------------|------------------------------------|---|------------------------------|
| ACECF                        | ACE<br>(Ashepoo, Combahee, Edisto) | Coastal Flatwoods<br>(or coastal plain) | 40                           |
| LSCF                         | Lower Santee                       | Coastal Flatwoods                       | 5                            |
| PDASLP                       | Pee Dee                            | Atlantic Southern Loam Plains           | 22                           |
| PDCF                         | Pee Dee                            | Coastal Flatwoods                       | 24                           |
| SALSH                        | Saluda (in Upper Santee)           | Sand Hills                              | 3                            |
| SAVSH                        | Savannah                           | Sand Hills                              | 4                            |

### *Aqueous Metals Results*

Dissolved metal concentrations varied widely. In order to identify sites with higher potential for ecotoxic effects, results were compared to USEPA values for Constant Contaminant Concentration (CCC) and Contaminant Maximum Concentration (CMC). The CCC and CMC are used as chronic and acute toxicity threshold values, respectively. The values were calculated using the water hardness at each site (from measured calcium and magnesium concentrations), but adjustments for natural organic matter (NOM) have not made. It should be noted that the USEPA has not published CCCs and CMCs for all metals analyzed. In total, 98 sites were sampled for 19 metals over spring, summer, and fall seasons in 2006 and 2007. The following discussion emphasizes sites for which metal concentrations exceeded CCC and CMC values.

Six metals (chromium, copper, lead, nickel, silver and zinc) were found to occur at concentrations exceeding CMC or CCC thresholds, however, only copper and lead were found in excess at a large number of sites. The remaining metals were below threshold values or there were no published values. Cadmium was found at a high concentration at one site (PDA-NAS), but is excluded because it is an outlier (13.4 µg/L vs. an average of 0.3 µg/L at 68 sites with cadmium detected). Table 2 lists sites that were found to exceed CMC and CCC values with the corresponding measured metal concentrations (ICP-MS) and threshold levels. It is apparent the metal concentration required to meet a threshold varies significantly, reflecting the variability in water chemistry. Water hardness ranged from 10 to 200 mg/L, with an average value of ~50. The copper CCC was exceeded at a total of thirty-nine sites with twenty-eight of those also exceeding the CMC. There were thirty sites above the lead CCC, but none exceeded the CMC. Eight sites were found to have nickel concentrations above the CCC with one exceeding the CMC. The chromium CCC and zinc CMC values were found to be exceeded at two sites. For silver, only a CMC threshold has been established and it was exceeded at one site.

There were several sites with multiple metals at concentrations above threshold values. At site ACE-NIC, chromium, copper, lead, and nickel were above the threshold concentrations with copper and nickel above CMC levels. Sites ACE-BLA2, ACE-GMC, PDC-CTS, PDC-TLR, PDA-NAS, and SAV-SAN each had three metals at or above threshold concentrations, and several other sites had two metals exceeding threshold values. While several sites show exceedances of a single metal, the data do support instances of metals co-occurrence and that a stream might be suffering from multiple impacts. It should be noted that the threshold values are markers for potential impairment; parameters including alkalinity, pH, and metal-binding ligands (e.g., NOM) can have profound effects on the toxicity of metals to aquatic systems.

**Table 2.** Sites with aqueous metal concentrations exceeding CCC and CMC thresholds. Measured and threshold metal concentrations shown in µg/L or ppb.

| Site                     | Measured | Threshold | Site                   | Measured | Threshold |
|--------------------------|----------|-----------|------------------------|----------|-----------|
| <b>Chromium (Cr) CCC</b> |          |           | <b>Lead (Pb) CCC</b>   |          |           |
| ACE-GMC                  | 151.00   | 108.50    | ACE-BLA1               | 0.45     | 0.41      |
| ACE-NIC                  | 76.90    | 32.15     | ACE-BLA2               | 4.31     | 2.70      |
| <b>Copper (Cu) CCC</b>   |          |           | ACE-BUC                | 0.72     | 0.26      |
| ACE-BAB2                 | 10.10    | 8.92      | ACE-CCC1               | 1.72     | 1.13      |
| ACE-BLA1                 | 2.46     | 2.19      | ACE-CLB                | 0.97     | 0.60      |
| ACE-BLA2                 | 13.90    | 9.63      | ACE-HMB                | 2.95     | 0.77      |
| ACE-CLB                  | 3.21     | 2.96      | ACE-JAB                | 0.50     | 0.28      |
| ACE-GMC                  | 15.50    | 13.47     | ACE-MCC                | 0.52     | 0.29      |
| ACE-SAN                  | 2.12     | 1.95      | ACE-NIC                | 2.71     | 0.84      |
| LSC-LSW                  | 3.94     | 3.34      | ACE-SAN                | 0.78     | 0.35      |
| PDA-TBS                  | 5.09     | 4.60      | ACE-SCC                | 0.74     | 0.29      |
| PDA-TLP1                 | 3.23     | 3.18      | ACE-TDS                | 1.00     | 0.30      |
| PDC-CAB                  | 3.97     | 3.61      | ACE-TRC                | 4.69     | 1.17      |
| PDC-CTS                  | 15.50    | 10.95     | LSC-LSW                | 1.86     | 0.69      |
| <b>Copper (Cu) CMC</b>   |          |           | PDA-BKS                | 0.61     | 0.58      |
| ACE-BUC                  | 2.92     | 1.86      | PDA-GUM                | 0.42     | 0.30      |
| ACE-HMB                  | 5.24     | 4.82      | PDA-MUH                | 0.75     | 0.48      |
| ACE-MCC                  | 3.45     | 2.06      | PDA-RCC1               | 0.73     | 0.43      |
| ACE-NIC                  | 14.00    | 5.16      | PDA-TGR                | 2.31     | 0.69      |
| ACE-TDS                  | 3.39     | 2.08      | PDA-TLP2               | 1.95     | 0.64      |
| PDA-BKS                  | 4.02     | 3.73      | PDC-CAB                | 1.18     | 0.77      |
| PDA-CAT                  | 9.19     | 4.34      | PDC-CAM                | 2.02     | 1.11      |
| PDA-CSC                  | 26.90    | 2.56      | PDC-CTS                | 3.54     | 3.18      |
| PDA-GUM                  | 4.52     | 2.10      | PDC-CYC                | 2.10     | 0.42      |
| PDA-HOM                  | 49.40    | 5.82      | PDC-KSC1               | 1.84     | 0.82      |
| PDA-MUD                  | 4.35     | 2.81      | PDC-NLR                | 9.79     | 0.56      |
| PDA-MUH                  | 4.55     | 3.19      | PDC-SIM2               | 15.70    | 2.36      |
| PDA-NAS                  | 34.50    | 5.14      | PDC-TLR                | 3.51     | 1.26      |
| PDA-RCC1                 | 9.23     | 2.88      | SAL-DBB                | 0.69     | 0.62      |
| PDA-TCT                  | 4.23     | 3.32      | SAV-SAN                | 0.32     | 0.18      |
| PDA-TGR                  | 14.00    | 4.33      | <b>Nickel (Ni) CCC</b> |          |           |
| PDA-TLP2                 | 5.00     | 4.08      | ACE-BAB2               | 228.00   | 50.47     |
| PDA-TMC                  | 4.63     | 2.25      | ACE-BLA2               | 252.00   | 54.52     |
| PDC-CYC                  | 4.57     | 2.84      | ACE-GMC                | 484.00   | 76.53     |
| PDC-KSC1                 | 6.28     | 5.09      | PDA-NAS                | 84.20    | 21.59     |
| PDC-NLR                  | 5.47     | 3.64      | PDC-CTS                | 156.00   | 62.07     |
| PDC-TCB                  | 7.76     | 6.52      | PDC-KSC1               | 47.40    | 21.41     |
| PDC-TKS                  | 13.00    | 6.44      | PDC-TLR                | 41.70    | 29.89     |
| PDC-TLR                  | 9.75     | 7.38      | <b>Nickel (Ni) CMC</b> |          |           |
| SAV-LHC                  | 1.96     | 1.73      | ACE-NIC                | 259.00   | 199.96    |
| SAV-SAN                  | 7.89     | 1.36      | <b>Silver (Ag) CMC</b> |          |           |
| SAV-TPS                  | 14.50    | 4.28      | ACE-CTC                | 1.14     | 0.84      |
| SAV-UTR                  | 1.87     | 1.86      | <b>Zinc (Zn) CMC</b>   |          |           |
|                          |          |           | PDA-NAS                | 98.30    | 50.36     |
|                          |          |           | SAV-SAN                | 24.30    | 15.49     |

### *Sediment Metals Results*

At present there are no definite sediment quality criteria defined by any regulatory agency in the US. It was therefore necessary to rely on literature reported threshold effects concentrations (TEC) and probable effects concentrations (PEC), however TECs and PECs are not available for all of the trace metals of interest (selenium, silver and thallium). MacDonald et al. (2000) reported threshold effects concentrations for the remaining seven trace metals (arsenic, cadmium, chromium, copper, lead, nickel, and zinc). Threshold effects concentrations are defined as the theoretical concentration at which toxic effects could begin to be observed. A probable effects concentration is defined as the concentration at which one is likely to observe toxic effects. Background values were taken from NOAA Screening Quick Reference Tables (Buchman 1999). Table 3 below presents available background, TEC, and PEC levels.

| <b>Table 3.</b> Background, TEC, and PEC values for sediment-associated metals. Concentrations in mg/kg. |                   |            |            |
|--|-------------------|------------|------------|
| <b>Metal</b>   | <b>Background</b> | <b>TEC</b> | <b>PEC</b> |
| Arsenic (Ar)   | 1.1               | 9.79       | 33.0       |
| Cadmium (Cd)   | 0.1-0.3           | 0.99       | 4.98       |
| Chromium (Cr)  | 7-13              | 43.4       | 111        |
| Copper (Cu)  | 10-25             | 31.6       | 149        |
| Lead (Pb)  | 4-17              | 0.18       | 128        |
| Nickel (Ni)  | 9.9               | 22.7       | 48.6       |
| Selenium (Se)  | 0.29              | *          | *          |
| Silver (Ag)  | 0.5               | *          | 4.5        |
| Zinc (Zn)  | 7-38              | 121        | 459        |

Each of the seven metals with reported TEC and PEC values was found at two or more sites at or above threshold effects concentrations, but no site exceeded a probable effects concentration. Table 4 lists sites found to exceed TECs and corresponding measured sediment concentrations. Lead exceeded the TEC at all sites except two. Arsenic and cadmium were found to exceed the TEC at two sites while there were three sites at which copper concentrations exceeded the TEC. The chromium TEC was exceeded at five sites, the nickel TEC at seven sites, and the zinc TEC at eight sites.

| <b>Table 4.</b> Sites with sediment-associated metals exceeding TECs. Measured concentrations and TECs in mg/kg. |          |                               |            |                            |          |
|--|----------|-------------------------------|------------|----------------------------|----------|
| Site   | Measured | Site                          | Measured   | Site                       | Measured |
| <b>Arsenic (As)</b> , TEC=9.79   |          | <b>Lead (Pb)</b> , TEC=0.18   |            | <b>Zinc (Zn)</b> , TEC=121 |          |
| ACE-TGS  | 12.91    | All except:                   |            | PDA-HHC2                   | 324.95   |
| PDC-PAL  | 9.88     | ACE-CNB                       | ND*        | PDA-MUD                    | 135.54   |
| <b>Cadmium (Cd)</b> , TEC=0.99   |          | ACE-CTC                       | ND         | PDA-MUH                    | 131.84   |
| ACE-TGS  | 1.59     | Data range all other sites:   |            | PDA-RCC1                   | 131.32   |
| PDA-NAS  | 2.68     |                               | 0.35-35.64 | PDA-RCC2                   | 167.05   |
| <b>Chromium (Cr)</b> , TEC=43.4  |          | <b>Nickel (Ni)</b> , TEC=22.7 |            | PDA-TCT                    | 128.66   |
| ACE-TGS  | 59.02    | ACE-BAB1                      | 24.61      | PDA-TGR                    | 139.00   |
| PDC-CAB  | 60.13    | ACE-SAW                       | 25.98      | SAL-LGB                    | 135.78   |
| PDC-NLR  | 685.43   | ACE-TGS                       | 25.60      |                            |          |
| PDC-TLR  | 43.78    | PDC-CAB                       | 34.45      |                            |          |
| PDC-WOB  | 1478.48  | PDC-NLR                       | 450.69     |                            |          |
| <b>Copper (Cu)</b> , TEC=31.6  |          | PDC-TLR                       | 30.14      |                            |          |
| PDA-HHC2   | 61.12    | PDC-WOB                       | 1672.55    |                            |          |
| PDA-RCC2   | 31.92    |                               |            |                            |          |
| PDC-WOB  | 63.65    |                               |            | *ND=Not detected.          |          |

Site ACE-TGS exceeded the threshold effects concentrations of five metals: arsenic, cadmium, chromium, lead, and nickel. Four sites in the PDCF ecobasin exceeded TEC levels for three or four metals: PDC-WOB (chromium, copper, lead, nickel) and PDC-CAB, PDC-NLR, and PDC-TLR (chromium, lead, and nickel). Two sites in the PDASLP ecobasin (PDA-HHC2, PDA-RCC2) exceeded TEC levels for copper, lead, and zinc. Compared to the aqueous metal concentration results, fewer sites were found to exceed metal toxicity guidelines, with the notable exception of lead.

#### *Correlations with Land Use*

Each set of measured metal concentrations was analyzed to determine possible relationships with land use in the watersheds and in a strip defined as the area extending to 100m either side of the stream and upstream of the sampling site. This report may refer to this as buffer, buffer strip, or buffer land, but this term does not imply a riparian buffer. ARC-GIS and United States Geological Survey (USGS) National Land Cover Data (NLCD) were used to define land use percentages based on the Land Use Survey conducted in 1992 and 2001. Seventeen land use

categories ranging from open land and barren rock to evergreen forests were grouped into four broader categories (development, forest, wetland, and agriculture) to simplify data analysis and increase land use percentages per category to above 1 percent. Compared to sites accessed in 2006, the watersheds sampled in the 2007 season had significantly less development and were dominated by forest and agriculture. This mismatch, and possibly the much drier weather conditions in 2007, has complicated analysis of the combined data sets. Efforts to analyze the full data set continue, but at this point results are presented for each sampling year separately. Due to the variability associated with studies of this nature, correlations with an  $r^2$  value greater than 0.10 and p value less than 0.05 were considered significant.

#### *2006 Land Use Results*

The 2006 land use parameters resulted in several correlations with agriculture, wetland, and forest land use coverage. Typically, positive correlations were observed with agriculture and wetland and negative correlations were observed with forest cover. Positive correlations with agricultural land use and negative correlations with forest cover are fairly easily understood, however, wetland correlations are more complex.

*Buffer Land Use.* The most significant single-metal correlations with land uses were observed in the buffer strip with dissolved metals. Correlations were observed with both nutrient metals (Mg and K) and trace metals. Positive correlations were observed with agricultural land use. Table 5 summarizes these correlations. Chromium is found at trace levels in many fertilizers and it is often used as a micronutrient in livestock operations. Phosphate fertilizers contain trace amounts of nickel and often metal parts of agricultural machinery are nickel-coated. Liu et al. (2007) found that the addition of phosphate and potassium fertilizers mobilized copper, chromium, and

nickel in soil. Correlations with lead may reflect long term agricultural uses of leaded fuel and lead arsenate as a pesticide.

| <b>Table 5.</b> Correlation results with buffer strip agriculture (2006) |                    |                      |                       |
|--|--------------------|----------------------|-----------------------|
| <b>Metal</b>   | <b>Land Use</b>    | <b>r<sup>2</sup></b> | <b>p</b>              |
| K (aq)   | Agriculture, strip | 0.40                 | <0.001                |
| Mg (aq)  | Agriculture, strip | 0.25                 | <0.01                 |
| Cr (aq)  | Agriculture, strip | 0.40                 | 1.28x10 <sup>-5</sup> |
| Ni (aq)  | Agriculture, strip | 0.24                 | 0.004                 |
| Pb (aq)  | Agriculture, strip | 0.22                 | 0.005                 |

Increasing forest cover in the buffer strip correlated with declining metal concentrations. Negative correlations with seven metals are summarized in Table 6. These trends are all consistent with forest cover preventing the mobilization of metals into aquatic systems.

| <b>Table 6.</b> Correlation results with buffer strip forest (2006) |                 |                      |                       |
|---|-----------------|----------------------|-----------------------|
| <b>Metal</b>  | <b>Land Use</b> | <b>r<sup>2</sup></b> | <b>p</b>              |
| K (aq)  | Forest, strip   | 0.40                 | 8.40x10 <sup>-5</sup> |
| Mg (aq)   | Forest, strip   | 0.25                 | 0.002                 |
| As (aq)   | Forest, strip   | 0.23                 | 0.003                 |
| Cr (aq)   | Forest, strip   | 0.19                 | 0.006                 |
| Ni (aq)   | Forest, strip   | 0.28                 | 0.001                 |
| Se (aq)   | Forest, strip   | 0.24                 | 0.01                  |
| Zn (aq)   | Forest, strip   | 0.13                 | 0.03                  |

Buffer wetlands showed a significant positive correlation with selenium, as summarized in Table 7. In reducing environments such as wetlands, hydrogen sulfide (H<sub>2</sub>S) and polysulfide ions (S<sub>n</sub><sup>2-</sup>) may react with selenium to produce selenium-substituted polysulfide anions (S<sub>n</sub>Se<sup>2-</sup>). These selenium containing ions are much more soluble and mobile than the slightly soluble selenate and selenite species. Also, sulfur-containing organic matter may exchange sulfur with selenium (Weres, Jaouni, & Tsao, 1989).

Significant sediment metal correlations were found only for silver with development, also summarized in Table 7.

| <b>Table 7.</b> Correlation results with selenium and silver (2006) |                    |                      |                       |
|---|--------------------|----------------------|-----------------------|
| <b>Metal</b>  | <b>Land Use</b>    | <b>r<sup>2</sup></b> | <b>p</b>              |
| Se (aq)   | Wetland, strip     | 0.37                 | 0.002                 |
| Ag (sed)  | Development, strip | 0.46                 | 1.49x10 <sup>-5</sup> |

*Total Watershed Land Use.* At each site the watershed is defined as the area upstream draining immediately into the stream. Significant correlations were observed with nutrient metals and trace metals, but were typically not as strong as correlations with the buffer strip land use. Table 8 summarizes these results.

| <b>Table 8.</b> Correlation results with total watershed land use (2006) |                 |                      |                       |
|--|-----------------|----------------------|-----------------------|
| <b>Metal</b>   | <b>Land Use</b> | <b>r<sup>2</sup></b> | <b>p</b>              |
| K (aq)   | Agriculture     | 0.40                 | 6.39x10 <sup>-5</sup> |
| Mg (aq)  | Agriculture     | 0.35                 | 2.46x10 <sup>-5</sup> |
| As (aq)  | Agriculture     | 0.16                 | 0.01                  |
| Cr (aq)  | Agriculture     | 0.11                 | 0.03                  |
| Ni (aq)  | Agriculture     | 0.24                 | 0.003                 |
| Se (aq)  | Agriculture     | 0.14                 | 0.04                  |
| K (aq)   | Forest          | 0.28                 | 0.001                 |
| Mg (aq)  | Forest          | 0.24                 | 0.003                 |
| Se (aq)  | Wetland         | 0.17                 | 0.03                  |
| Ag (sed)   | Development     | 0.50                 | 4.78x10 <sup>-6</sup> |
| Ag (sed)   | Agriculture     | 0.15                 | 0.015                 |

Agricultural land uses in the watersheds showed the largest number and strongest correlations. As with buffer strip land use, nutrient metals tended to show the strongest relationships with agriculture whereas trace metal correlations are weaker. Forest cover in watersheds showed correlations only with the nutrient metals and as with buffer forest, these correlations were negative. Only selenium was found to have a dependence on wetlands in the watershed. As before, selenium showed a positive correlation with percent wetland. Sediment metals produced very few correlations with land use and again only with silver. However, there were two significant and positive correlations with agriculture and development.

#### *2007 Land Use Results*

The 2007 land use results produced no significant correlations with metal concentrations. This is due to the fact that there was very little variation in the land use parameters from site to site. As stated above development was significantly less than 2006 thus reducing the variability in the watersheds and making analysis difficult. Despite the relative lack of development in the

watersheds of sites sampled in 2007, variations in metal concentrations were observed, as evidenced by the occurrence of several ACE basin sites in Tables 2 and 4. Therefore, simply combining data sets from 2006 and 2007 did not strengthen correlations observed for 2006 data. These results may indicate that important effects are not captured appropriately in the land use data (e.g., historical effects or very recent effects) or that effects unrelated to land use are significant (e.g., ground water surface water exchange, atmospheric deposition). Continuing analyses will investigate these possibilities as well as analysis of the data by ecobasin in order to restrict comparisons to areas with more similar ecosystem characteristics and histories.

#### *Principle Components Analysis*

Principle Components Analysis (PCA) was used to elucidate possible interrelated components of the land use data set and to emphasize the key components or factors in correlations with metal concentration results. Principal components allows for a combination of independent variables, such as land use, resulting in dimensional reduction of the data set to 3 or 4 variables, and thus (ideally) simplifying analyses and interpretation of the data set. At this point, principal components has been performed only on the total data set (2006 and 2007) using total watershed land use data.

Three measures were used to determine the number of components retained: the eigenvalue-one criterion (retain principal components with an eigenvalue  $\geq 1$ ), the cumulative proportion of variance accounted for (retain if  $\geq 70\%$ ), and individual proportion of variance accounted for (retain if  $\geq 10\%$ ). In the application of PCA to all watershed land use data applicable to all sites sampled in 2006-2007, each of the four principal components (PC) described below met at least two of the three retention criteria, and each showed a significant proportion of cumulative percent of variance accounted for.

|  |
|--|
| <b>Table 9.</b> Retention criteria for each PC |
|--|

| PC | Eigenvalue | Fraction of variance | Fraction of cumulative variance |
|----|------------|----------------------|---------------------------------|
| 1  | 3.9498     | 0.3291               | 0.3291                          |
| 2  | 2.5167     | 0.2094               | 0.5385                          |
| 3  | 1.7023     | 0.1419               | 0.6804                          |
| 4  | 1.2234     | 0.1020               | 0.7824                          |

| <b>Table 10. Eigenvectors describing each PC</b> |             |             |             |             |
|--|-------------|-------------|-------------|-------------|
|  | <b>PC 1</b> | <b>PC 2</b> | <b>PC 3</b> | <b>PC 4</b> |
| Dev. Open  | 0.451884    | 0.065520    | -0.059683   | 0.006622    |
| Dev. Low   | 0.486112    | -0.081194   | 0.100233    | 0.038424    |
| Dev. Med   | 0.466311    | -0.139574   | 0.117779    | 0.047246    |
| Dev. High  | 0.474886    | -0.127341   | 0.108929    | 0.028153    |
| Deciduous For.                                   | 0.028985    | 0.502625    | 0.318917    | -0.016496   |
| Evergreen For.                                   | -0.212244   | -0.218511   | 0.504598    | -0.179261   |
| Mixed For.                                       | -0.080667   | 0.356415    | 0.346952    | -0.043748   |
| Woody Wet.                                       | -0.225058   | -0.416445   | -0.090426   | 0.110668    |
| Herbaceous Wet.                                  | -0.069875   | -0.201202   | 0.185464    | 0.584728    |
| Grassland  | -0.099603   | 0.257221    | 0.121043    | 0.683307    |
| Pasture  | 0.039440    | 0.440888    | -0.027167   | -0.333073   |
| Cultivated Crops                                 | -0.005314   | 0.232906    | -0.652677   | 0.170668    |

It can be seen that PC1 to PC4 generally correspond to 1) development, 2) non-evergreen forests and pastures, 3) forests, and 4) wetlands and grasslands, respectively. Two significant correlations, one with PC1 and one with PC3, were found. Magnesium (aq) was shown to be positively related to PC1 ( $r^2=0.101$ ,  $p=0.0015$ ) while potassium (aq) was negatively related to PC3 ( $r^2=0.108$ ,  $p=0.0009$ ). These results show in part the power of PCA to reduce the number of components or effects considered. More significantly, the results confirm the small number of significant correlations obtainable for the full 2006-2007 data set. Thus the need for further analyses incorporating additional components (e.g., ground water influences) and ecobasin specific analysis is clear and such analyses are ongoing.

## ACKNOWLEDGEMENTS

A project and sampling program such as this requires the combined efforts of many people, but particular acknowledgement of extraordinary effort is due to Kevin Kubach, SCDNR, for field

logistics, and Cathy Marion, Clemson University, for collation of land use data. We also thank Dr. Patrick Gerard, Clemson University, Dept. Applied Economics and Statistics, for assistance with PCA.

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## Appendix A. Site Abbreviation Key and Sampling Dates

| Site Abbreviation | Ecobasin | Name/Description of Stream                 | Date Sampled |
|-------------------|----------|--|--------------|
| ACE-BAB1          | ACECF    | Bachelor Branch                            | 11-Jul-2007  |
| ACE-BAB2          | ACECF    | Bachelor Branch                            | 11-Jul-2007  |
| ACE-BCB           | ACECF    | Baptist Church Branch                      | 11-Sep-2007  |
| ACE-BHR           | ACECF    | Bull Head Run                              | 27-Jun-2007  |
| ACE-BLA1          | ACECF    | Black Creek                                | 21-Jun-2007  |
| ACE-BLA2          | ACECF    | Black Creek                                | 12-Sep-2007  |
| ACE-BRB           | ACECF    | Bush Branch                                | 20-Jun-2007  |
| ACE-BUC           | ACECF    | Buckhead Creek                             | 2-Aug-2007   |
| ACE-CCC1          | ACECF    | Cow Castle Creek                           | 11-Jul-2007  |
| ACE-CCC2          | ACECF    | Cow Castle Creek                           | 12-Jul-2007  |
| ACE-CLB           | ACECF    | Colston Branch                             | 1-Aug-2007   |
| ACE-CNB           | ACECF    | Canady Branch/Broad Ax Branch              | 28-Jun-2007  |
| ACE-CTC           | ACECF    | Cowtail Creek                              | 31-Aug-2007  |
| ACE-DBC           | ACECF    | Deep Bottom Creek                          | 29-Aug-2007  |
| ACE-FIS           | ACECF    | Fishburne Creek                            | 23-Aug-2007  |
| ACE-FSW           | ACECF    | Fullers Swamp Creek                        | 20-Jul-2007  |
| ACE-GMC           | ACECF    | Gantts Mill Creek                          | 28-Jun-2007  |
| ACE-HMB           | ACECF    | Halfmoon Branch                            | 3-Aug-2007   |
| ACE-IRE           | ACECF    | Ireland Creek                              | 2-Aug-2007   |
| ACE-JAB           | ACECF    | Jackson Branch                             | 29-Aug-2007  |
| ACE-JSC           | ACECF    | Jones Swamp Creek                          | 2-Aug-2007   |
| ACE-LWB           | ACECF    | Little Walnut Branch                       | 12-Jul-2007  |
| ACE-MCC           | ACECF    | Mechaw Creek                               | 29-Jun-2007  |
| ACE-MLC           | ACECF    | Mill Creek/Cane Gully Branch               | 28-Jun-2007  |
| ACE-NIC           | ACECF    | Nicholson Creek                            | 23-Aug-2007  |
| ACE-PKS           | ACECF    | Polk Swamp                                 | 18-Jul-2007  |
| ACE-SAN           | ACECF    | Sanders Branch                             | 18-Jul-2007  |
| ACE-SAV           | ACECF    | Savannah Creek                             | 12-Sep-2007  |
| ACE-SAW           | ACECF    | Sawmill Branch                             | 30-Aug-2007  |
| ACE-SCC           | ACECF    | Scotts Creek                               | 19-Jul-2007  |
| ACE-TDB           | ACECF    | tributary to Deep Branch                   | 12-Sep-2007  |
| ACE-TDS           | ACECF    | tributary to Drayton Swamp                 | 21-Jun-2007  |
| ACE-TGS           | ACECF    | tributary to Great Swamp                   | 12-Sep-2007  |
| ACE-TIM           | ACECF    | Timothy Creek                              | 30-Aug-2007  |
| ACE-TKB           | ACECF    | Tom and Kate Branch                        | 24-Aug-2007  |
| ACE-TLS           | ACECF    | tributary to Little Salkehatchie River     | 11-Sep-2007  |
| ACE-TMS           | ACECF    | tributary to Middle Pen Swamp              | 22-Jun-2007  |
| ACE-TRC           | ACECF    | tributary to Rantowles Creek/Drayton Swamp | 19-Jul-2007  |
| ACE-TUR           | ACECF    | Turkey Creek                               | 21-Jun-2007  |
| ACE-TWR           | ACECF    | tributary to Wando River                   | 20-Jun-2007  |
| LSC-LSW           | LSCF     | Little Swamp                               | 23-Jun-2006  |
| LSC-TCC           | LSCF     | tributary to Cedar Creek                   | 22-Jun-2006  |
| LSC-TLM           | LSCF     | tributary to Lake Marion                   | 27-Jun-2007  |
| LSC-TMC           | LSCF     | tributary to Mechaw Creek                  | 21-Jun-2006  |
| LSC-WTB           | LSCF     | Wee Tee Branch                             | 22-Jun-2006  |
| PDA-BKS           | PDASLP   | Back Swamp                                 | 28-Sep-2006  |
| PDA-CAT           | PDASLP   | Catfish Canal                              | 3-Aug-2006   |
| PDA-CNB           | PDASLP   | Cane Branch                                | 10-Aug-2006  |
| PDA-CSC           | PDASLP   | Cane Savannah Creek                        | 2-Aug-2006   |

|          |        |                                    |             |
|----------|--------|------------------------------------|-------------|
| PDA-GUM  | PDASLP | Gum Swamp                          | 17-Aug-2006 |
| PDA-HHC1 | PDASLP | High Hill Creek                    | 9-Aug-2006  |
| PDA-HHC2 | PDASLP | High Hill Creek                    | 18-Aug-2006 |
| PDA-HOM  | PDASLP | Home Branch                        | 2-Aug-2006  |
| PDA-MUD  | PDASLP | Muddy Creek                        | 16-Aug-2006 |
| PDA-MUH  | PDASLP | Mush Branch                        | 23-Aug-2006 |
| PDA-NAS  | PDASLP | Nasty Branch                       | 4-Aug-2006  |
| PDA-RCC1 | PDASLP | Rogers Creek Canal                 | 8-Sep-2006  |
| PDA-RCC2 | PDASLP | Rogers Creek Canal                 | 3-Aug-2006  |
| PDA-TAB  | PDASLP | tributary to Alligator Branch      | 10-Aug-2006 |
| PDA-TBS  | PDASLP | tributary to Bear Swamp            | 14-Sep-2006 |
| PDA-TCT  | PDASLP | tributary canal to Tobys Creek     | 17-Aug-2006 |
| PDA-TGR  | PDASLP | tributary to Gully Run             | 16-Aug-2006 |
| PDA-TLP1 | PDASLP | tributary to Little Pee Dee River  | 14-Sep-2006 |
| PDA-TLP2 | PDASLP | tributary to Little Pee Dee River  | 24-Aug-2006 |
| PDA-TMB  | PDASLP | tributary to Martins Branch        | 25-Aug-2006 |
| PDA-TMC  | PDASLP | tributary to Muddy Creek           | 7-Sep-2006  |
| PDA-WOC  | PDASLP | White Oak Creek                    | 24-Aug-2006 |
| PDC-BCR1 | PDCF   | Buck Creek                         | 31-May-2007 |
| PDC-BCR2 | PDCF   | Buck Creek                         | 31-May-2007 |
| PDC-CAB  | PDCF   | Canaan Branch                      | 15-May-2007 |
| PDC-CAM  | PDCF   | Camp Branch                        | 4-May-2007  |
| PDC-CTS  | PDCF   | Crab Tree Swamp                    | 17-May-2007 |
| PDC-CYC  | PDCF   | Cypress Creek                      | 13-Jun-2007 |
| PDC-DAM  | PDCF   | Big Dam Swamp                      | 14-Jun-2007 |
| PDC-DOB  | PDCF   | Dobson Branch                      | 9-May-2007  |
| PDC-HBR  | PDCF   | Horse Branch                       | 2-May-2007  |
| PDC-KSC1 | PDCF   | Kingstree Swamp Canal              | 10-May-2007 |
| PDC-KSC2 | PDCF   | Kingstree Swamp Canal              | 22-Aug-2007 |
| PDC-NLR  | PDCF   | Negro Lake Run                     | 16-May-2007 |
| PDC-PAL  | PDCF   | Palmetto Swamp                     | 16-May-2007 |
| PDC-SIM2 | PDCF   | Simpson Creek                      | 1-Jun-2007  |
| PDC-SIM2 | PDCF   | Simpson Creek                      | 31-May-2007 |
| PDC-SVC  | PDCF   | Savannah Creek                     | 13-Jun-2007 |
| PDC-TBS  | PDCF   | tributary to Big Swamp             | 3-May-2007  |
| PDC-TCB  | PDCF   | Tearcoat Branch                    | 30-May-2007 |
| PDC-TKC  | PDCF   | tributary to Kingstree Swamp Canal | 8-May-2007  |
| PDC-TKS  | PDCF   | tributary to Kingstree Swamp Canal | 8-May-2007  |
| PDC-TLR  | PDCF   | tributary to Lynches River         | 3-May-2007  |
| PDC-TRB  | PDCF   | Trestles Branch                    | 2-May-2007  |
| PDC-WIT  | PDCF   | Withers Swash                      | 14-Jun-2007 |
| PDC-WOB  | PDCF   | White Oak Bay                      | 9-May-2007  |
| SAL-DBB  | SALSH  | Double Branch                      | 31-May-2006 |
| SAL-LGB  | SALSH  | Long Branch                        | 25-May-2006 |
| SAL-TWC  | SALSH  | Twelvemile Creek                   | 25-May-2006 |
| SAV-LHC  | SAVSH  | Little Horse Creek                 | 7-Jun-2006  |
| SAV-SAN  | SAVSH  | Sand River                         | 7-Jun-2006  |
| SAV-TPS  | SAVSH  | tributary to Polk Swamp            | 14-Jun-2006 |
| SAV-UTR  | SAVSH  | Upper Three Runs                   | 8-Jun-2006  |

## Assessing suspended sediment transport potential and supply in an urbanizing coastal plains stream

### Basic Information

|                                 |  |
|---------------------------------|--|
| <b>Title:</b>                   | Assessing suspended sediment transport potential and supply in an urbanizing coastal plains stream |
| <b>Project Number:</b>          | 2008SC55B  |
| <b>Start Date:</b>              | 3/1/2008   |
| <b>End Date:</b>                | 2/28/2009  |
| <b>Funding Source:</b>          | 104B   |
| <b>Congressional District:</b>  | First  |
| <b>Research Category:</b>       | Not Applicable   |
| <b>Focus Category:</b>          | Models, Sediments, Geomorphological Processes  |
| <b>Descriptors:</b>             | None   |
| <b>Principal Investigators:</b> | Anand Jayakaran, Susan Libes   |

### Publication

1. Owens K. J., and A. D. Jayakaran. 2008. Modeling Channel Maintenance Strategies in a Coastal Plain Watershed, in South Carolina Water Resources Conference 2008. North Charleston, South Carolina (October 2008).

# **Assessing suspended sediment transport potential and supply in an urbanizing coastal plains stream**

A Project Report  
for  
SOUTH CAROLINA WATER RESOURCES CENTER  
SOUTH CAROLINA COMPETITIVE GRANTS PROGRAM

August 2009

Anand D Jayakaran. PhD. Asst. Professor, Biosystems Engineering  
Clemson University

Susan R Libes. PhD. Professor, Marine Chemistry  
Coastal Carolina University

Kelly J Owens. MS. Former Grad. Research Asst., Biosystems Engineering  
Clemson University

## **B: Executive Summary**

Non-point source pollution is an issue that seriously impacts the use of the state's water resources for aquatic life use, recreational use, and for shell fish consumption. Almost 60% of the State's rivers appear on the 303(d) list of polluted waters for bacterial pollution; further impairment by suspended sediments is also widely seen in many of the water courses. The Crabtree Canal is located in an urbanizing watershed, currently on the 303(d) list for fecal coliforms. The stream was also on the 303(d) list for dissolved oxygen in 2000. An analysis of data measured over the last two years at a USGS gage located at the watershed outlet shows that dissolved oxygen and turbidity are still sources of impairment in the Crabtree Canal. Principal sediment inputs are landscape sources due to land development activities, in-channel sources as a consequence of channel maintenance activities, and from bank instabilities due to increased peak flows that result from watershed urbanization. Evidence of bank instability and mass wasting is widely seen in the Crabtree Canal system. The watershed has undergone considerable urbanization in the last few decades.

The overall objectives of this study were to:

1. Determine temporal distribution of suspended sediment transport rates at a point in the Crabtree Canal.
2. Determine spatial distribution of sources that supply sediments to the main stem of Crabtree Canal.
3. Relate sediment contributions to organic loadings in the Crabtree Canal.
4. Develop a hydrodynamic model for Crabtree Canal to model changes in flow regime and sediment transport capacity with alternative channel configurations.

In conjunction with determining the temporal distribution of suspended sediments for five storm events, the spatial distribution of suspended sediment in the Crabtree Canal watershed was also assessed. Additionally, the quantification of the amount of organic material associated with sediments shed some light on the dissolved oxygen impairment measured in Crabtree Canal.

A one dimensional hydrodynamic tool was developed as a working management tool to determine hydrodynamic conditions on the watershed driven by hypothetical storm events and alternative ditch management techniques. The model will be delivered to the Horry County stormwater department to determine potential zones of stream instability, and evaluate alternate stream management techniques. Changes in flow regime were quantified as alterations to flow stages, and average channel velocity; changes in sediment transport capacity quantified in terms of changes in stream power, and average shear stresses on the channel bed and banks.

The hydrodynamic model that was developed was used to determine alternative floodplain configurations, and the impacts of these alternatives on hydrodynamics with the drainage system. It was shown that increases in floodplain ratio resulted in a significant decrease in total shear stress, average flow velocity, and hydraulic depth. The

provision of greater floodplain was directly correlated to the decrease in the above-mentioned variables. The greatest decrease in these variables with floodplain width was in the upstream reaches, with less pronounced effects in the downstream reaches of the system. This study suggested that in the upstream reaches, a floodplain ratio greater than five was needed to ensure that a critical shear stress threshold was not exceeded.

## **C: Introduction and Background**

The management of South Carolina's coastal streams has attained critical status, as burgeoning development places increasing demands on riparian ecosystems. Increased runoff rates, sediment loads and attending water quality impairment have proved to be a great challenge to those that seek to preserve and maintain the integrity of riparian ecosystems in the region.

The low gradient, shallow water table, coarse-grained watersheds of coastal South Carolina present a unique hydrologic landscape to the urban planner, stormwater control and other regulatory agencies, and land stewards of the State. Regional hydrologic conditions coupled with the rapid rate of development evidenced in recent history pose a unique set of challenges for the people that live, work, and play in this region. Residential development, industrial operation, and tourism related commercial activities have seen explosive growth in recent decades (Tufford et al., 2003). The negative impacts of development upon riparian functioning have been widely documented in various geographic settings and at multiple spatial scales. (e.g. Martens, 1968; Krug and Goddard, 1986; Booth, 1990; Schueler, 1994; Booth and Jackson, 1997; White and Greer, 2006).

Coastal watersheds in South Carolina are the second largest destination for tourists, only exceeded by Florida (Allen et al., 1999). A greater understanding of the hydrologic alterations to the unique coastal landscape of South Carolina would facilitate the development of more effective, sustainable, and low impact best management practices to both protect human life and maintain essential ecological services.

In order to arrive at a better understanding of the flow and suspended sediment dynamics in coastal plains watersheds, two streams from extreme ends of the development spectrum were monitored for flow and suspended sediment loading rates. While the two watersheds were monitored under separate research studies, suspended sediment information derived from these projects offer a framework for comparison of urban and undeveloped watersheds in a low gradient coastal plains landscape. While neither watershed is completely urbanized or completely pristine, the study watersheds are fairly representative of the two ends of the development spectrum as seen in coastal South Carolina. At the urban end of the development spectrum, Crabtree Canal is located in Horry County, SC with about 24% of its watershed area developed or cultivated (based on LULC NLCD 2002) ; at the undeveloped end is Debidue Creek, which is located in Georgetown County, SC (Figure 1) with land cover classified as woody wetlands, herbaceous scrub or evergreen forest. The dissimilarities between the two watersheds allows for a comparison over a large range of stream morphology and landuse type.

### ***Study area***

Crabtree Canal is a subwatershed of the Waccamaw River and is a third order stream with a drainage area of approximately 70 km<sup>2</sup> (27 mi<sup>2</sup>) at its confluence with the Kingston Lake Swamp drainage network (Figure 1). 18.2% of the land is developed;

25.4% of the land is forested; 30.6% of the land is pasture or cultivated crops and 25.8% of the land is classified as wetlands. The dominant soil type present in the study site are Meggett loams and Wahee fine sandy loams, that are poorly draining soils characterized as hydrologic type D soils. In all, hydrologic group D soils cover over half of the watershed 28% of the soils were type C soils, 11 % of the soils were type B soils and 7% of the soils were type A soils.

Crabtree Canal is currently on the 303(d) list for fecal coliforms, and appeared on the list for dissolved oxygen (DO) for 2000. High turbidities following rain events are being recorded by a USGS sensor on the Crabtree Canal (USGS 02110701 Crabtree Swamp at Conway, SC). An analysis of turbidity data recorded between 9/26/05 to 12/17/07 at this gage showed that daily mean values for turbidity contravened the SC DHEC water quality standard (50 NTU) 10% of the time. This would put the site at 'level of concern' per TMDL criteria. If the US EPA recommended standard of 4 NTU's was applied, the site would be substandard for 97% of the days analyzed. An US EPA 319 project (Libes and Bennet, 2004) also found high SSC/VSS loading following rain events. It is likely that with higher frequency turbidity sampling at the EPA recommended standard, the Crabtree Canal would be considered impaired with respect to suspended sediments. A similar analysis of daily mean DO for the same time period showed the SC DHEC water quality standard was contravened for 23% of the days analyzed. The Crabtree Canal could therefore be classified as being at a level of concern for both turbidity and dissolved oxygen.

Evidence of bank instability and mass wasting is widely seen in the Crabtree Canal system. The watershed has undergone considerable urbanization in the last few decades. A consequence of urbanization is increases in peak and volume of stormwater runoff. The consequences of hydrologic regime alteration on the receiving stream are channel instability, down cutting and widening of the channel; typically accompanied by bank instability and bank erosion. The Crabtree Canal was originally channelized to drain wetlands for the production of agriculture. This process of is often repeated with earth moving equipment used to dredge the bottom of the channel to conform to standard engineering design.

The downstream reaches of Crabtree Canal are tidally influenced and are also affected by backwater effects from the much larger Waccammaw River into which Kingston Lake Swamp flows just 3.7 km downstream of its confluence with Crabtree Canal (Figure 1). In order to remedy urban flooding problems in Conway, the US Army Corps of Engineers straightened and reshaped the channel to a large trapezoidal shape. These channel modifications disconnected the channel from its natural floodplain. The excavated soil was piled up along the channel and further disconnected the floodplain from the main channel. Crabtree Canal currently exhibits characteristics of a Rosgen Type F or G channel (Rosgen, 1994).

Due to the increase in sediments and sediment deposition, periodic channel dredging was carried out to maintain the ability of the channel to convey the increased stormwater discharges associated with an urbanizing watershed. This periodic dredging reshaped the

channel and removed any rooted vegetation along the boundaries of the channel. Principal sediment inputs today are likely from landscape sources and in-channel sources; however, a more accurate estimate of sediment sources is lacking. Evidence of bank instability and in channel erosion is widely seen in the Crabtree Canal system.

A study was initiated by Clemson University in partnership with Coastal Carolina University to evaluate suspended sediment yields from this urbanizing watershed, to identify sources of sediment within the drainage network, and develop a tool that would be useful to stormwater agents that manage and maintain Crabtree Canal.

The specific objectives of this project was to: (1) determine the temporal distribution of suspended sediment transport rates at a point in the Crabtree Canal, (2) determine the spatial distribution of sources that supply sediments to the main stem of Crabtree, (3) relate sediment contributions to organic loadings in the Crabtree Canal, and (4) develop a hydrodynamic model for Crabtree Canal in the Kingston Lake Watershed to model changes in flow regime and sediment transport capacity with alternative channel configurations.

Some of the data were also collected as part of a long-term monitoring program that supports the NPDES Phase II stormwater programs being conducted by Horry County and the City of Conway. This monitoring work is coordinated with SC DHEC's monthly monitoring and involves biweekly sampling of a number of other water quality parameters. Data are provided to the public at: [http://bcmw.coastal.edu/river\\_gauge/](http://bcmw.coastal.edu/river_gauge/). The USGS monitoring station (02110701) is similarly funded and purposed. Data are provided to the public at: <http://waterdata.usgs.gov/nwis/uv?02110701>. Horry County also provided funding for geographic surveys to ascertain sources of bacteria (fecal coliforms) and sediment within the drainage basin. Additional water quality parameters were measured as part of these surveys.

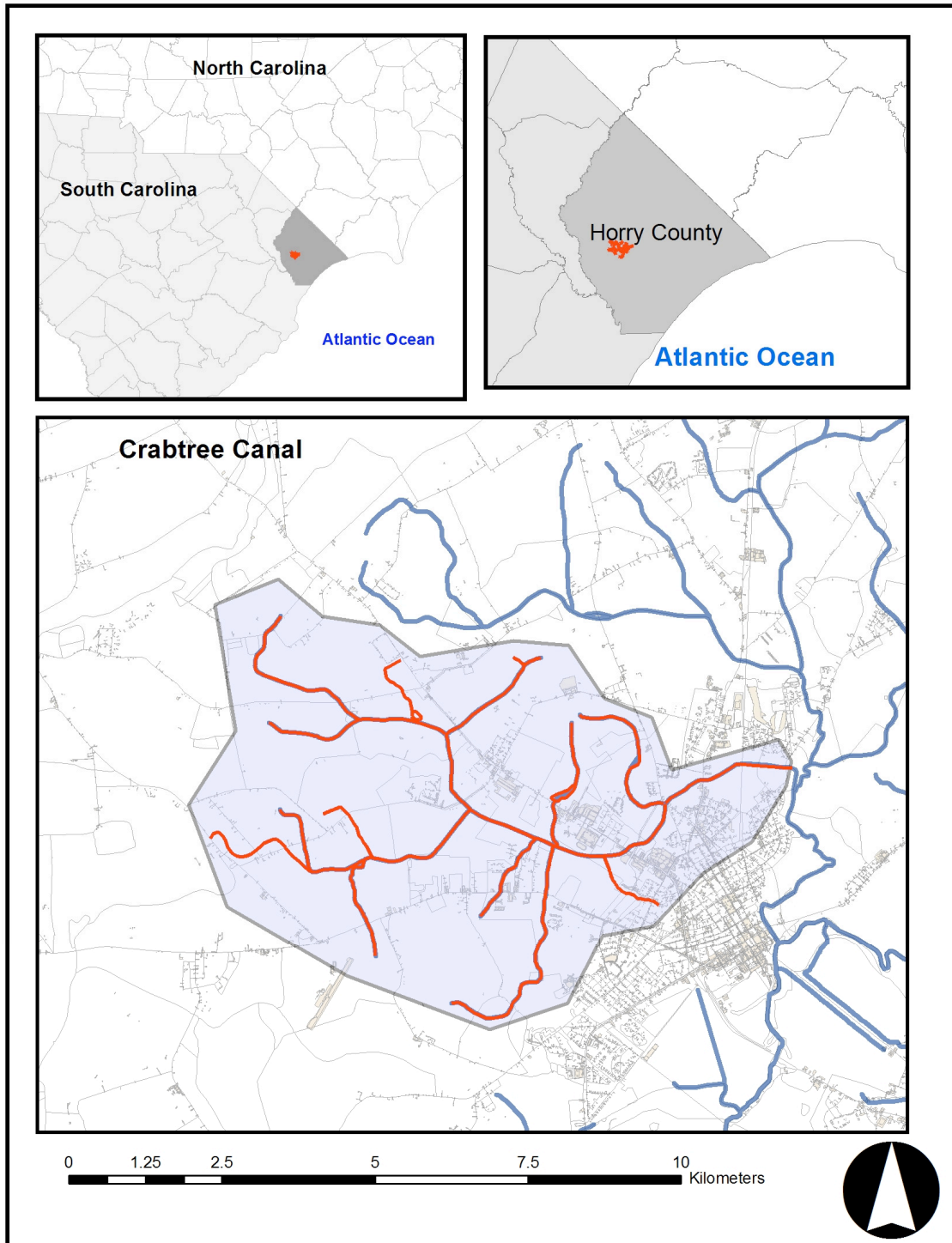


Figure 1: Map of the Eastern coast of South Carolina showing the location of Crabtree Canal.

## **C: Methodology**

### ***Flow measurement***

Flow and suspended sediment measurements in Crabtree Canal were generated by the USGS. A USGS real-time gaging station (USGS 02110701) is located in proximity and upstream of its confluence with the Kingston Lake Swamp. The gage is located at the bridge crossing of Crabtree Canal by Long Avenue. The drainage area is 46 km<sup>2</sup> and the datum of the gage is 3 m (USGS, 2009). The gage is located about 0.5 km upstream from the confluence of Crabtree Canal and the Kingston Lake Swamp drainage network. Parameters of stream flow of interest to this study and available for public download are: stage, average velocity, rainfall, and turbidity; data measured at 15-minute intervals. Discharge data (not published to the website) were obtained for the entire period of record directly from USGS, and comprised raw discharge that reflect the semi-diurnal tidal variation at the gaging station, and filtered data. Filtered data were obtained by passing raw discharge data through a low-pass filter algorithm developed by USGS.

### ***Suspended Sediment Sample collection***

Three types of sampling were conducted: Samples obtained from an autosampler that comprised grab sampling during storm events, biweekly depth-integrated grab sampling, and a basin-wide of grab samples during wet and dry weather.

#### ***Autosampler: Grab sampling during storm events***

Grab sampling was conducted using an ISCO ® 6712 autosampler deployed from the southern stream bank of Crabtree Canal near the bridge at Long Avenue. Five storm events were sampled using the sampler programmed to collect time-paced composite samples, triggered by rainfall above a predefined intensity threshold. The sampler was programmed to collect 250ml aliquots every 30 minutes, with four aliquots composited per sample bottle and representing two hours of suspended sediment flux in the canal; the time between the first and last sample collected was 48 hours. Intake nozzle of the sampler was set at an elevation of about 0.5m above the stream bed. At the time of retrieval of the sample bottles after a storm event, an additional sample was collected via the autosampler intake nozzle. Simultaneously, a depth integrated isokinetic sample was collected mid-channel from a bridge deck adjacent to the sampling site.

#### ***Basin-wide grab samples during wet and dry weather***

Six surveys were conducted by sampling 16 sites located in the tributaries and main stem of Crabtree Canal upstream of Long Avenue. Three surveys were done within 24 hours of a significant rain event and three were done during dry weather. Sites sampled were located in the major tributaries and in the main stem so as to isolate the geographic sources of SSC. Details of the site locations, sampling dates and rain accumulations are shown in Tables 3 and 4. Depth-integrated samples were collected where depths exceeded 0.3 m. Where depth-integrated sampling was not possible due to restricted water depths, samples were collected by submerging a sampling bottle and allowing it to fill.

### *Biweekly depth-integrated grab sampling*

Depth-integrated sampling was conducted midstream at Long Avenue on a biweekly basis. Samples were collected from the bridge over Crabtree Canal using a USGS depth integrating sampler (Wading Type- US DH-48). The vertically integrated samples were obtained provided averaged SSC at the time of sample collection within the Canal. The biweekly grab sampling conducted from the bridge at Long Avenue was part of another project which also supports the measurement of fecal coliform, BOD, nutrient and chlorophyll concentrations.

### *Suspended sediment loading*

The fraction of SSC that comprised organic material was estimated for all samples. Continuous turbidity data measured at 15 minute intervals by the USGS at Crabtree Canal allowed for the estimation of annual suspended sediment yield at that site. Since five storm events were sampled, five paired measurements of SSC at the intake, and depth averaged SSC were obtained. A linear regression function derived from these five data pairs, was used to estimate a depth averaged SSC value for every corresponding sample collected via the automatic sampler over the 48-hour period of sampling. This relationship had the form:

$$SSC_{canal} = a(SSC_{intake}) + b \quad (1)$$

Where:  $SSC_{canal}$  is the depth averaged suspended sediment concentration in the canal  
 $SSC_{intake}$  is the suspended sediment concentration derived from the autosampler.  
 $a, b$ , are regression coefficients.

Another relationship between suspended sediments measured in the canal and turbidity in the canal was also developed and was of the form:

$$SSC_{canal} = c(Turbidity_{canal}) + d \quad (2)$$

Where:  $Turbidity_{canal}$  is the measured turbidity in NTU's as recorded by the USGS instream turbidity sensor.  
 $c, d$  are regression coefficients

The relationship of suspended sediment concentrations with measured discharge was examined for statistical significance. Suspended sediment concentrations were also multiplied with raw discharge values to obtain instantaneous loading rates. These instantaneous loading rates were then integrated over the period of record using the partial balance method (Probst, 1986), resulting in an estimate of total suspended sediment yield from the watershed:

$$Tm = \sum_1^n [C(\Phi)Q(\Phi)t(\Phi)] \quad (3)$$

Where  $Tm$  is monthly suspended sediment tonnage,  $n$  is number of phases (each phase corresponds to the period between two consecutive stage observations).

$C(\Phi)$ ,  $Q(\Phi)$ , and  $t(\Phi)$  are average concentration, average discharge, and duration of each phase.

Dry and storm event grab samples were also collected at 16 locations (Table 1 and Figure 2). These sites were sampled following 3 storm events and 3 times during dry weather in the Crabtree Canal to characterize instantaneous SSC during low flow and storm conditions at various locations in the contributing watershed.

Table 1. Locations and descriptions of spatial survey sampling sites in Crabtree Swamp drainage basin, Horry County, SC

| <i>Field Site Descriptions</i> |                          | <i>Sample Collection Point</i>  |                 |                  |
|--------------------------------|--------------------------|---|-----------------|------------------|
| <i>Site ID</i>                 | <i>Site Location</i>     | <i>Description</i>  | <i>Latitude</i> | <i>Longitude</i> |
| 17 NC2                         | Ned Creek and Hwy 548    | Pipe under road, sampled on downstream end of pipe                                  | 33°52'22" N     | 79°06'33" W      |
| 16 FM                          | Fourmile Rd and Hwy 501  | Pipe under road, sampled on downstream end of pipe                                  | 33°52'02" N     | 79°05'55" W      |
| 15 SS                          | Sioux Swamp Drive        | Bridge crossing, sampled on downstream side   | 33°51'47" N     | 79°06'01" W      |
| 14 DS                          | Dunn Shortcut            | Bridge crossing, sampled on downstream side   | 33°51'23" N     | 79°05'53" W      |
| 13 OS                          | Oakey Swamp at Dayton Dr | Sampled in stream 10-15 m upstream from canal                                       | 33°51'19" N     | 79°05'50" W      |
| 12 WR                          | West Rd                  | At road end, sampled near stormwater runoff pipe                                    | 33°51'08" N     | 79°05'20" W      |
| 11 AB                          | Altman Branch            | Box culvert under Hwy 378, sampled upstream end                                     | 33°50'33" N     | 79°05'01" W      |
| 10 WT                          | Wiegand Timber           | Pipe under Hwy 501, sampled downstream end  | 33°51'27" N     | 79°05'06" W      |
| 8 TG                           | Tiger Grand              | Sampled in wetland across Hwy 501 from large pond                                   | 33°51'21" N     | 79°04'57" W      |
| 9 P                            | Pond on Hwy 501          | Sampled in pond next to outlet weir   | 33°51'23" N     | 79°04'56" W      |
| 7 MPS                          | Mill Pond Stream         | Sampled in stream ~5 m upstream from canal  | 33°51'57" N     | 79°04'10" W      |
| 6 H501                         | Hwy 501                  | Box culvert under Hwy 501, sampled upstream end                                     | 33°51'57" N     | 79°04'10" W      |
| 4 OS                           | Oak Street               | Bridge crossing, sampled on downstream side, tributary stream enters upstream       | 33°51'21" N     | 79°03'45" W      |
| 3 H701                         | Hwy 701                  | Box culvert under Hwy 701, sampled upstream end                                     | 33°51'32" N     | 79°03'22" W      |
| 2 LA                           | Long Avenue              | Bridge crossing, sampled on downstream side, stormwater runoff pipe enters upstream | 33°51'39" N     | 79°02'28" W      |
| 1 CC                           | Country Club Avenue      | Bridge crossing, sampled on upstream side   | 33°51'50" N     | 79°02'20" W      |

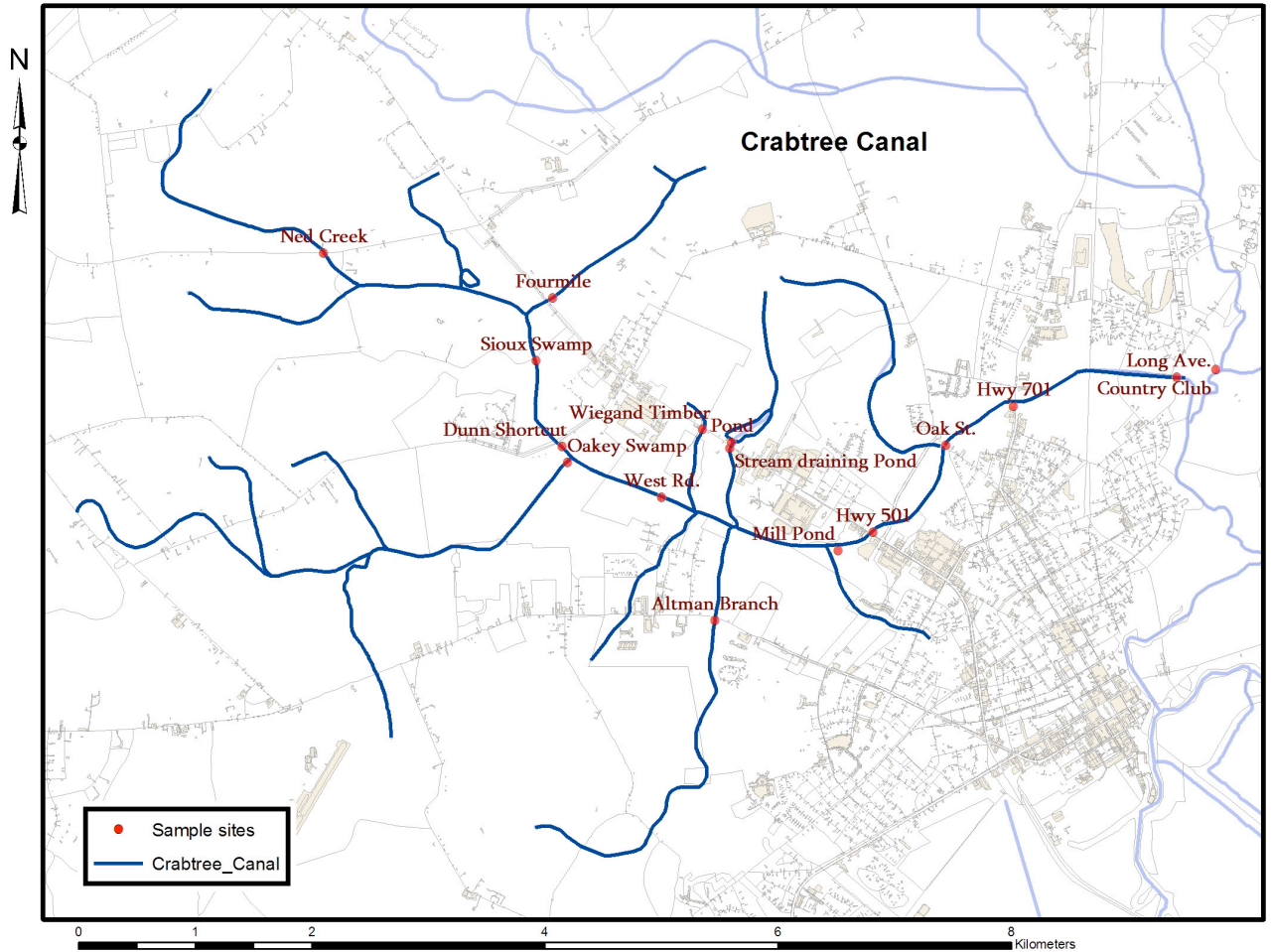


Figure 2. Sites used for spatial sampling of SSC in the Crabtree watershed.

### ***Development of 1-dimensional hydraulic model***

A one-dimensional hydraulic model was developed to serve as a tool to evaluate hydrodynamic conditions within the Canal system driven by a hypothetical storm events and alternative channel geometry configurations. The model was also developed to quantify the relative performance of different floodplain configurations, to identify possible zones of instability in Crabtree Canal, and to identify the most suitable locations and size for floodplain alteration. HEC-RAS was chosen due to the relative ease of use and customization, wide-spread usage in the engineering community, and its availability without cost.

The location of the gage was chosen as the downstream extent of the physical domain that was to be modeled. The upstream extent in both physical and computational domains was at Four Mile Road (see Figure 3), approximately 9,500 m (31,000 ft) upstream of the Long Avenue Bridge. Three tributaries were also modeled. Figure 3 provides the extent of the modeled reaches and those reaches that were not included in the one-dimensional model.

Within a Geographic Information System (GIS) environment, Light Detection and Ranging (LiDAR) data was used to develop a digital terrain model (DTM) both as a Triangulated Irregular Network (TIN) and as a raster format. The DTM was applied to the watershed and the surrounding area. A stream centerline layer was then added. The centerline was broken up by reaches and tributaries in the drainage network. Centerlines were drawn from upstream to downstream. Junction points connected each tributary to the main stem. After establishing the locations of the centerlines, each reach and tributary was assigned a unique reach and river name. Cross sections were extracted from the DTM at regular intervals along the length of the modeled system. These cross sections were only representative of the land above the water surface as LiDAR does not penetrate below the water surface. Manual topographic surveys were performed to determine below-water channel morphology.

Two different types of surveys were done. On both surveys a laser level was used to take an elevation reading at a point that was easily distinguishable on the LiDAR dataset such as a bridge deck or other high point. One method used an elevation reading to the water surface and then took depth readings to determine the bottom of channel geometry, while the other directly measured the entire channel cross section using a laser level set up at a known elevation. Water depth readings were taken at several points along the channel bed using a simple measuring rod. The geographic position of each depth reading was recorded with a hand held Trimble®<sup>1</sup> GPS unit as they were taken. Channel bed elevation readings were taken at all bridge crossings. Topographic surveys were conducted on head water reaches to determine general channel shape and profile. Elevations measured along the channel thalweg helped determine the approximate slope of the channel. The latter survey method was used in the upstream sections of the system where the water depth was shallower. Channel depth readings taken from the surveys were interpolated to approximate channel bottom geometry along the entire channel. Cross sections previously taken from the LiDAR data were altered in HEC RAS to include the bottom of the channel as well as the terrain above the water surface.

A total of 12 bridges and culverts were included in the model (Figure 4). Dimensions of the modeled bridges were obtained from the Horry County office of the South Carolina Department of Transportation (Patrick, 2008).

#### *Data sources*

Modeling in general has greatly improved in recent years with the advancement of geographic information systems (GIS), radar-based rainfall estimation using next generation radar (NEXRAD), high resolution digital elevation models (DEMs), distributed hydrologic and hydraulic models, and the online delivery systems by which information is made available (Knebl et al., 2005).

Different types of models and tools were compiled to form a collective, more comprehensive model. The compilation of tools for this project included ESRI's

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<sup>1</sup> 2005 Trimble® GeoXT

ArcMap™, USDA's WinTR-55, and HEC-RAS (ArcMap™ and WinTR-55 were used to derive input data for HEC-RAS).

For this study, hydrographs were obtained using Win TR-55 computer program. WinTR-55 models single rainfall and direct surface runoff events; available online from NRCS (USDA) (<http://www.nrcs.usda.gov/>). WinTR-55 uses the TR-20 (NRCS, 2002) model for all of the hydrograph procedures: generation, channel routing, storage routing, and addition; it does not model inputs from groundwater or ice. Crabtree is located in a coastal region of South Carolina where water tables are relatively high.

Land use data for this study were obtained from the National Land Cover Database (MRLC, 2009) dataset. NLCD is a land cover database produced by the Multi-Resolution Land Characteristics Consortium, an effort by several federal agencies to provide the nation with digital land cover and ancillary data (MRLC, 2009). Information pertaining to the soils in the watershed was obtained from Web Soil Survey (WSS) (<http://websoilsurvey.nrcs.usda.gov>). Table 3 summarizes the data sources utilized by this project as well as the data source.

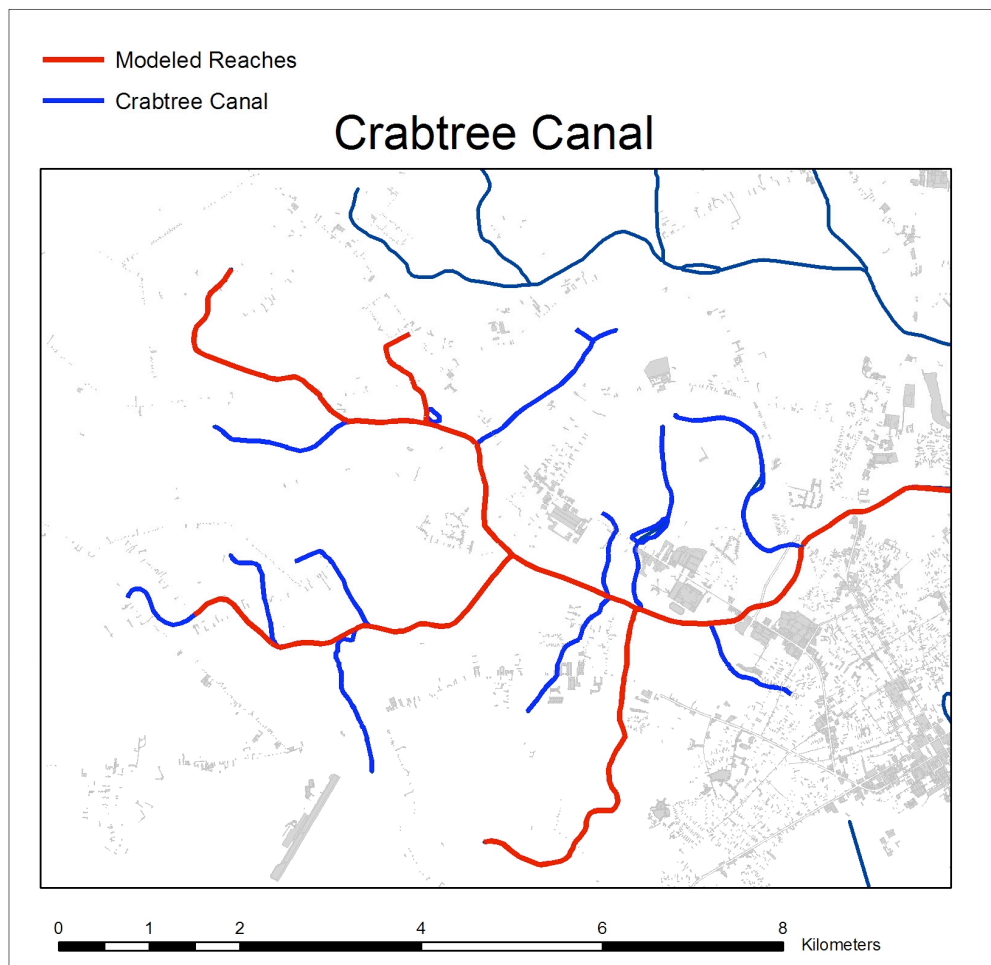


Figure 3. Schematic showing the Crabtree Canal network and reaches modeled.

Table 3. Data sources utilized and the respective data obtained.

| Data Source                  | Data Obtained                         |
|------------------------------|---------------------------------------|
| National Land Cover Database | Land use data                         |
| Web Soil Survey              | Soil information                      |
| Geospatial Data Gateway      | DEM used to delineate watershed areas |

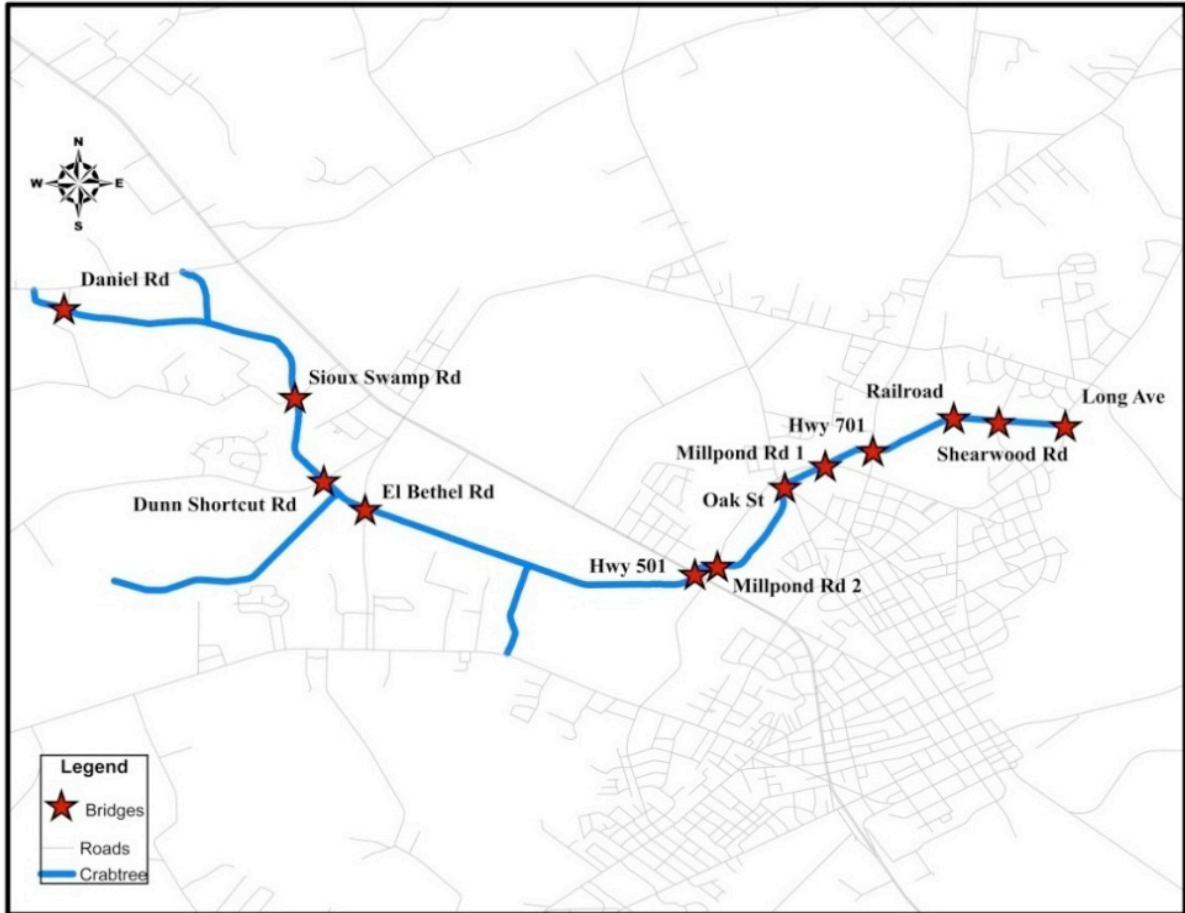


Figure 4. Map of bridges and culverts included in the model.

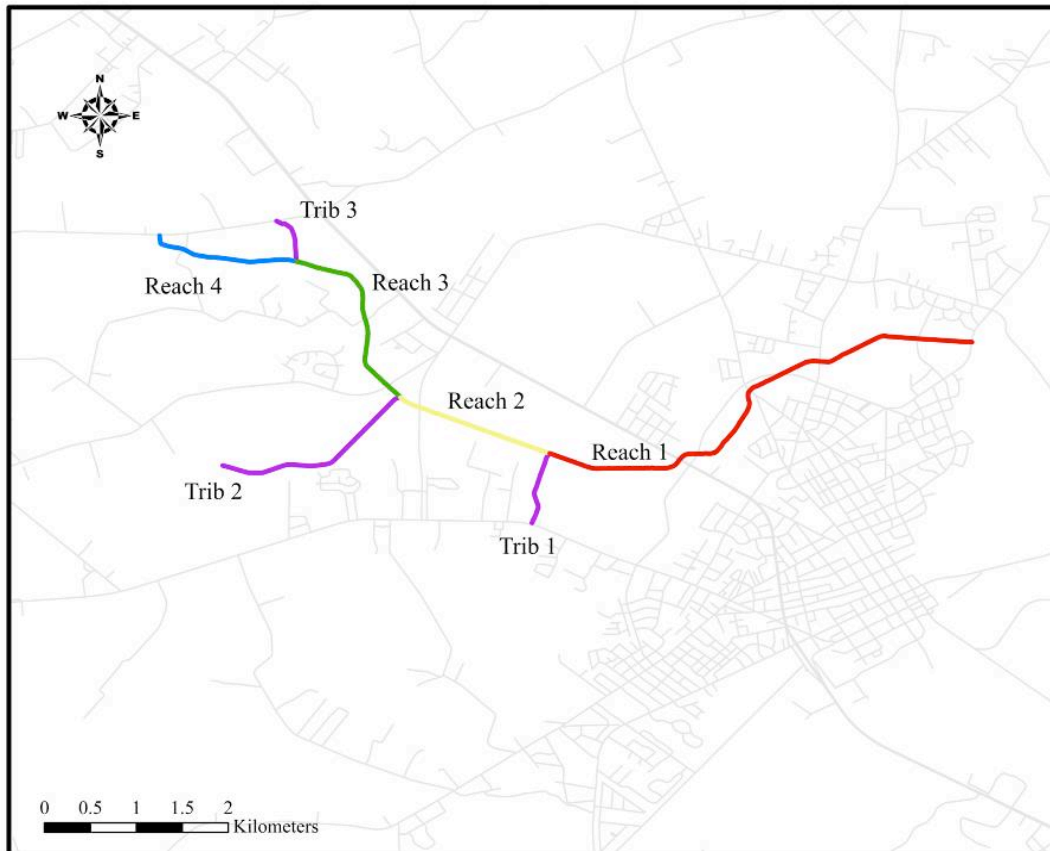


Figure 5. Schematic of reaches and tributaries that were modeled.

### *Hydrograph generation*

Hydrographs were generated using WinTR-55, a single event rainfall-runoff small watershed hydrological model. The watershed was broken up into subareas and reaches. Subareas and reaches either drain to other reaches, or to the watershed outlet. For this model, the outlet was set at the Long Avenue Bridge at Crabtree Canal (downstream extent of Reach 1 in Figure 5).

Flow hydrographs were used to define boundary conditions at inflow points to the model. These inflow points corresponded to the upstream-most extent of the Canal which is at Reach 4 and at the upstream ends of all the tributary reaches (See Figure 5). Within WinTR-55, subareas were defined that drained into the tops of the tributaries and the top of Reach 4. Watershed areas were delineated within a GIS environment using ArcHydro<sup>®</sup> (Maidment, 2003) and a digital elevation model (DEM) of the study region. The DEM was obtained in raster format from the Geospatial Data Gateway (<http://datagateway.nrcs.usda.gov/GatewayHome.html>), a website hosted and maintained by the United States Department of Agriculture (USDA). The DEM used in this study was of 30-meter spatial resolution and part of the National Elevation Dataset (NED). The National Land Cover Database (MRLC, 2009) was used as a source of land cover information for the study region. Land cover data were downloaded as digital raster files from the National Map Seamless Survey (<http://seamless.usgs.gov/>), a website hosted and maintained by the United States Geological Survey (USGS). The dataset comprises a raster dataset of 50-meter spatial resolution, each pixel representing a specific land use. Land cover in the Crabtree Canal watershed and those subwatersheds that contribute to flow in the four modeled tributaries were estimated using an overlay function of watershed extent and land cover data.

WinTR-55 was used to obtain flow hydrographs used for unsteady flow analysis with HEC-RAS. Different rainfall events can be chosen to produce various hydrographs. The unsteady flow data used to run simulations in this study corresponded to a storm with a return period between 2 and 5 years. A rainfall distribution type III was used (SCS, 1986). WinTR-55 was used to generate hydrographs for the top of each tributary and the top of Reach 6. Hydrographs were generated using land use details, soil types and rainfall data for the study area. The design storm event that was used to compare floodplain configurations was chosen such that there was used at least 0.15m (0.5ft) depth of water over the floodplain for the widest floodplain modeled. This was undertaken as unsteady flow simulations with HEC RAS tended to go unstable if flow depths on the floodplain dropped below this level.

### *Channel modification*

A two-stage channel design modification was applied to Reaches 1, 2, and 3 (Figure 5). The tributaries that were included in the model were not modified (See Figure 6). Flood plain width was quantified using a measure called Floodplain Ratio (FPR) and was used to evaluate different channel configurations with increasing floodplain widths. The FPR is defined as the ratio of the flooded width, to the main channel width (Figure 6). FPR values greater than 2 require providing or widening the floodplain. Floodplain ratios of 2, 3, 5, 7, 10 and 20 were modeled to give a range of results. Because the Canal is such a

modified and incised system, finding reference bankfull features to model where the natural flood plain may form was extremely challenging. However, at one reach close to the watershed outlet (between Millpond Bridge 2 and Oak St Bridge), an incipient floodplain was observed. This floodplain was approximately 1.1 m (3.6 ft) above the channel bed. The discharge that would produce a depth of flow of 1.1 m (3.6 ft) at this point was found and was used to determine the depth of flow in the other reaches of the system. The depth of the main channel of the two-stage design was made to corresponded to the depth of flow that coincided with the incipient floodplain. A steady discharge of 4.6 m<sup>3</sup>/s (162 cfs) at Long Avenue Bridge is the flow that corresponded to a 1.1 m (3.6 ft) flow depth at the proposed modification site. WinTR-55 was used to determine what proportion of the total flow (4.6 m<sup>3</sup>/s, flow at Long Avenue. Bridge) was contributed by each of the tributaries.

Crabtree is an excavated channel that is periodically dredged; it is of earthen base, straight and uniform; hence a Manning's n value of 0.022 (based on Chow, 1959) was used for the main channel. Depending on if and what of kind vegetation is planted on the floodplain after reconfiguration, the Manning's n value would change on the floodplain. After modification, native plants and trees would be planted on the floodplain so a light brush with trees condition would be present on the floodplain. Chow (1959) suggests a minimum Manning's n of 0.04 for a light brush with trees condition. The minimum value was chosen because immediately after reconfiguration the vegetation wouldn't be very thick and would inflict the minimum amount of friction on overbank flows.

The side slopes of the main channel would not be disturbed below the top of the main channel. Excavation would only be done to alter the floodplain. A 2:1 side slope was used from the floodplain elevation to the original channel. According to USDA (2007) the angle of repose for a Meggett loam (dominate soil type) is 32.5° therefore a 2:1 side slope would be acceptable. The original channel bed elevation was not changed. Unsteady flow simulations were performed for the following floodplain configurations:

- a) The existing geometry,
- b) Floodplain ratio of 2,
- c) Floodplain ratio of 3
- d) Floodplain ratio of 5
- e) Floodplain ratio of 7
- f) Floodplain ratio of 10
- g) Floodplain ratio of 20

Mean velocities (Equation 3), average depth of flow, the average shear stress (Equation 2) exerted on the channel boundaries and a weighted average shear stress (total shear stress) (Equation 4) across the width of the channel at each cross section were chosen to quantitatively compare the different simulated floodplain configurations. Over the course of the unsteady flow simulation, the mean velocity, hydraulic depth and shear stress was

noted at the point in time when the water surface elevation was the maximum for each cross section. An average of the values at each cross section was calculated for each modified reach. The minimum and the maximum values for mean velocity, hydraulic depth and shear stress were also recorded for each modified reach.

Total shear stress across the width of the channel is calculated by:

$$\bar{\tau} = \frac{\sum_{i=1}^n l_i \tau_i}{\sum_{i=1}^n l_i} \quad (4)$$

Where:  $\bar{\tau}$  = total shear stress (N/m<sup>2</sup>) and  
 $\tau_i$  = shear stress per unit cross sectional width (N/m<sup>2</sup>)  
 $l_i$  = Unit cross sectional width (m).

While stream bed elevation is determined by the balance between sediment supply and the sediment transport capacity, channel stability requires that the shear stress exerted by discharge remain below the critical shear stress of the channel bed (Clark and Wynn, 2007). Critical shear stress was calculated for the channel bed by using a method outlined in NRCS's Stream Restoration Design National Engineering Handbook (USDA-NRCS, 2007). Critical shear stress thus calculated was compared to shear stress imposed upon the floodplain and channel as predicted by HEC RAS in order to determine where potential zones of instability are in the system.

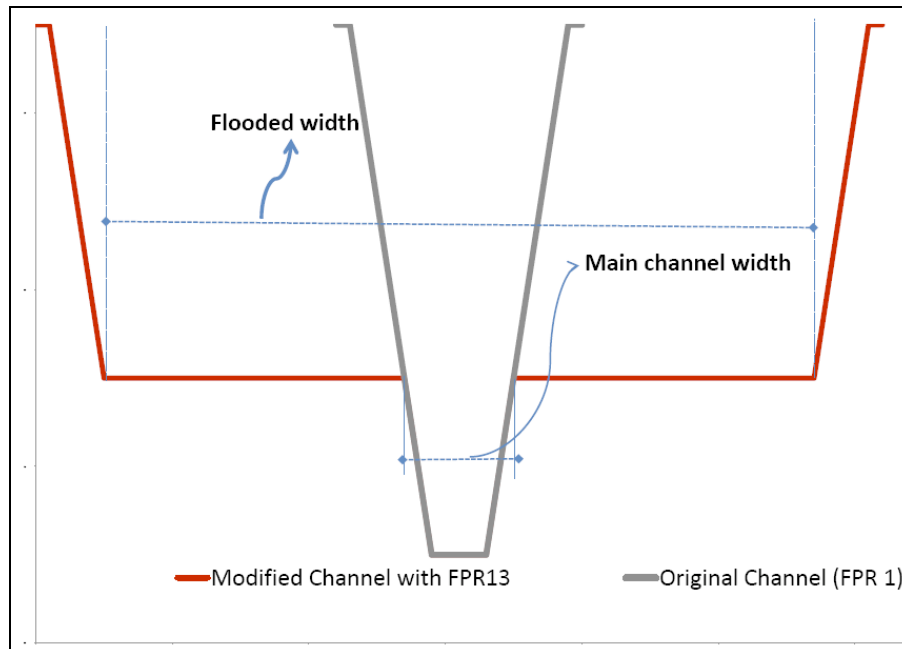


Figure 6. Schematic showing the original channel, and a modified configuration with a floodplain ratio of 13 (FPR=13).

## D: Results and Conclusions

### *Temporal distribution of suspended sediments*

Grab sampling was conducted using an ISCO autosampler deployed from the southern stream bank of Crabtree Canal near the bridge at Long Avenue during five storm events. A graphical representation of the variation in measured suspended sediment concentration with turbidity for the five storm events are plotted in Figure 7. Details of the sampling conducted during each event are provided in Table 4. Depth-integrated sampling was conducted midstream at Long Avenue on a biweekly basis. Samples were collected from the bridge over Crabtree Canal using a depth integrating sampler. Sampling dates and rainfall information are provided in Table 5 along with results of interest to this report.

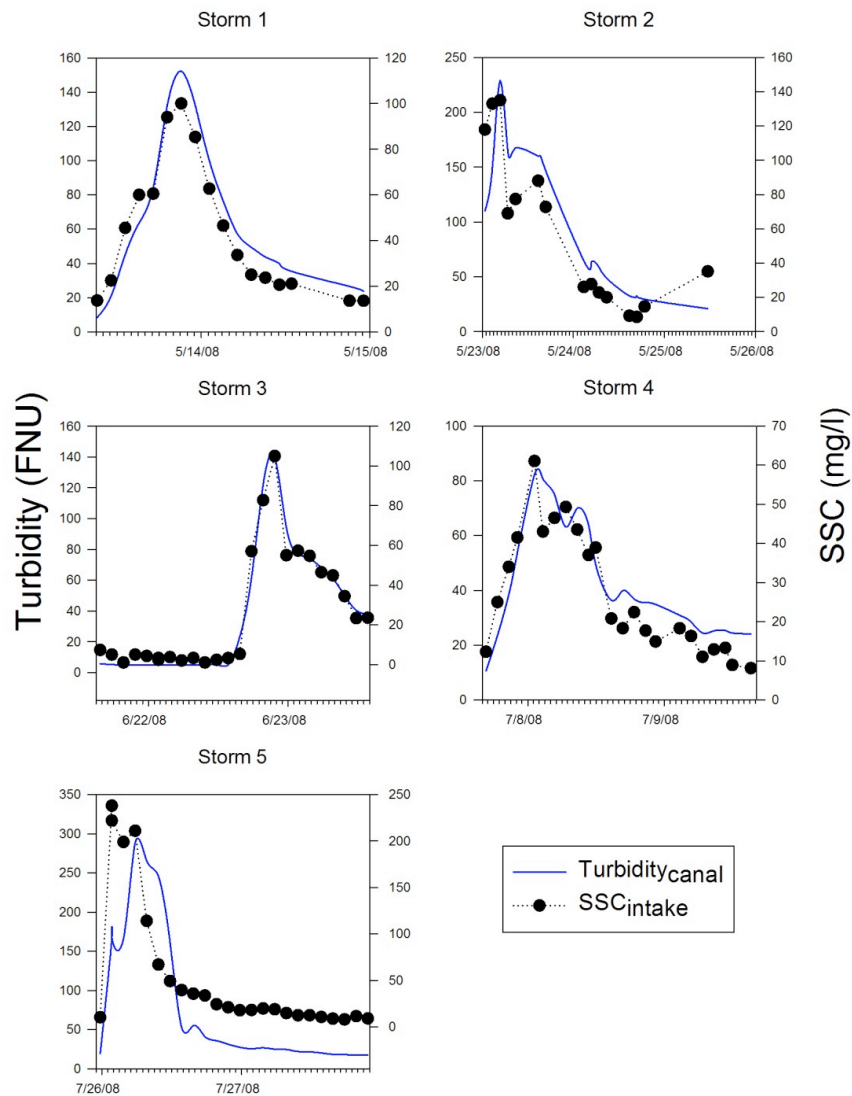


Figure 7. SSC sampled obtained via the autosampler and measured in-stream turbidity values for five storm events during the summer of 2008.

Table 4. Wet weather sampling conducted with an ISCO autosampler deployed from the southern stream bank of Crabtree Canal near the Long Avenue. bridge. Table provides details on sampling conducted following each rain event.

| # SSC<br>Samples | <i>Start</i> |             | <i>End</i>  |             | <i>Rain</i>          |               | <i>Gage Discharge (cfs)</i> |            |            |                                   | <i>Gage Height (ft)</i> |            |            |                                   | <i>Turbidity (NTU)</i> |            |            |                                   |
|------------------|--------------|-------------|-------------|-------------|----------------------|---------------|-----------------------------|------------|------------|-----------------------------------|-------------------------|------------|------------|-----------------------------------|------------------------|------------|------------|-----------------------------------|
|                  | <i>Date</i>  | <i>Time</i> | <i>Date</i> | <i>Time</i> | <i>Rain<br/>(in)</i> | <i>Period</i> | <i>Start</i>                | <i>Max</i> | <i>End</i> | <i>Event<br/>Max<br/>Increase</i> | <i>Start</i>            | <i>Max</i> | <i>End</i> | <i>Event<br/>Max<br/>Increase</i> | <i>Start</i>           | <i>Max</i> | <i>End</i> | <i>Event<br/>Max<br/>Increase</i> |
| 17               | 5/11/08      | 9:09        | 5/17/08     | 23:09       | 1.25                 | 5/11          | -18                         | 73         | -16        | 91                                | 10.22                   | 11.37      | 10.41      | 1.15                              | 5                      | 160        | 14         | 155                               |
| 14               | 5/21/08      | 0:44        | 6/22/08     | 18:46       | 1.04                 | 5/20-5/21     | -11                         | 37         | -18        | 48                                | 10.21                   | 10.88      | 10.2       | 0.67                              | 13                     | 220        | <5         | 207                               |
| 25               | 6/20/08      | 15:45       | 6/21/08     | 13:43       | 1.80                 | 6/19-6/21     | -17                         | 39         | 100        | 56                                | 10.13                   | 10.75      | 11.07      | 0.62                              | <5                     | 81         | 150*       | 76                                |
| 23               | 7/5/08       | 16:41       | 7/7/08      | 15:11       | 0.78                 | 7/5-7/7       | -77                         | 59         | -12        | 136                               | 9.91                    | 10.61      | 9.6        | 0.70                              | 9.2                    | 92         | 23         | 82.8                              |
| 25               | 7/23/08      | 23:43       | 7/25/08     | 21:43       | 1.81                 | 7/23-7/24     | -6                          | 266        | 0          | 272                               | 9.95                    | 11.45      | 10.01      | 1.50                              | 27                     | 325        | 15         | 298                               |

Table 5: River Gaging Data: Grab Sample from Bridge at Long Avenue.

| <i>Date</i>       | <i>SSC<br/>(mg/L)</i> | <i>VSS<br/>(mg/L)</i> | <i>Turbidity<br/>(NTU)</i> | <i>%VSS</i> | <i>BOD<sub>5</sub><br/>(mg/L)</i> | <i>FC<br/>(CFU/100<br/>mL)</i> |
|-------------------|-----------------------|-----------------------|----------------------------|-------------|-----------------------------------|--------------------------------|
| 1/31/2008         | 2.3                   | 0.9                   | 7                          | 39%         | 2.1                               | 8                              |
| 1/31/2008**       | 2.6                   | 0.8                   | 7                          | 31%         | 2.1                               |                                |
| 2/13/2008         | 52.0                  | 8.0                   | 80                         | 15%         | 4.6                               | 55                             |
| 2/27/2008         | 11.7                  | 2.4                   | 40                         | 21%         | 3.3                               | 50                             |
| 3/12/2008         | 10.7                  | ND                    | 23                         | ND          | 2.1                               | 50                             |
| 3/27/2008         | 6.1                   | 1.6                   | 35                         | 26%         | 1.1                               | 23                             |
| 4/10/2008         | 7.1                   | 1.4                   | 17                         | 20%         | 1.3                               | 23                             |
| 4/10/2008*        | 7.4                   | 1.7                   | 17                         | 23%         | 1.3                               |                                |
| 4/23/2008         | 5.1                   | 1.8                   | NA                         | 35%         | 1.0                               | 17                             |
| 4/23/2008*        | 7.6                   | 2.8                   | NA                         | 37%         | 1.0                               |                                |
| 5/7/2008          | 3.9                   | 1.0                   | 7                          | 26%         | 1.3                               | 80                             |
| 5/22/2008         | 18.0                  | 2.6                   | 39                         | 14%         | 2.1                               | 75                             |
| 6/4/2008          | 6.0                   | 1.8                   | NA                         | 30%         | 0.9                               | 17                             |
| 6/4/2008*         | 4.6                   | 1.6                   | NA                         | 35%         | 0.9                               |                                |
| 6/18/2008         | 8.0                   | 5.1                   | 8                          | 64%         | 3.9                               | 23                             |
| 7/16/2008         | 21.0                  | 5.0                   | 30                         | 24%         | 2.0                               | 130                            |
| 7/16/2008**       | 13.5                  | 2.0                   | 30                         | 15%         | 2.0                               | ND                             |
| 7/16/2008*        | 12.5                  | 2.5                   | 30                         | 20%         | 2.0                               | ND                             |
| *Autosampler grab |                       |                       | ND = not determined        |             |                                   |                                |
| **Field duplicate |                       |                       | NA = data not available    |             |                                   |                                |

A relationship between suspended sediment concentrations (SSC) from samples obtained via the automatic sampler intake nozzle, and depth averaged samples was established. Five paired SSC samples were used to estimate this bias. SSC of samples obtained from the intake were consistently higher than those samples that represented depth average samples. A linear regression derived using these data (Figure 8) yielded the following expression:

$$SSC_{canal} = 0.44SSC_{intake} + 3.48 \quad (R^2 = 0.89, p < 0.05) \quad (5)$$

The linear regression function was used to correct SSC readings obtained via the autosampler ( $SSC_{intake}$ ) that represented the entire storm hydrograph (SSC values depicted in Figure 7) in order to better reflect averaged SSC values ( $SSC_{canal}$ ). A simple scatter plot of measured turbidity and SSC values show a high correlation between SSC values and turbidity (Figure 9). A linear regression line explained 80% of variability in depth averaged SSC values ( $SSC_{canal}$ ) with change in turbidity in the canal ( $R^2 = 0.80, p < 0.05$ ) and was of the form:

$$SSC_{canal} = 0.30(Turbidity_{canal}) + 3.2 \quad (6)$$

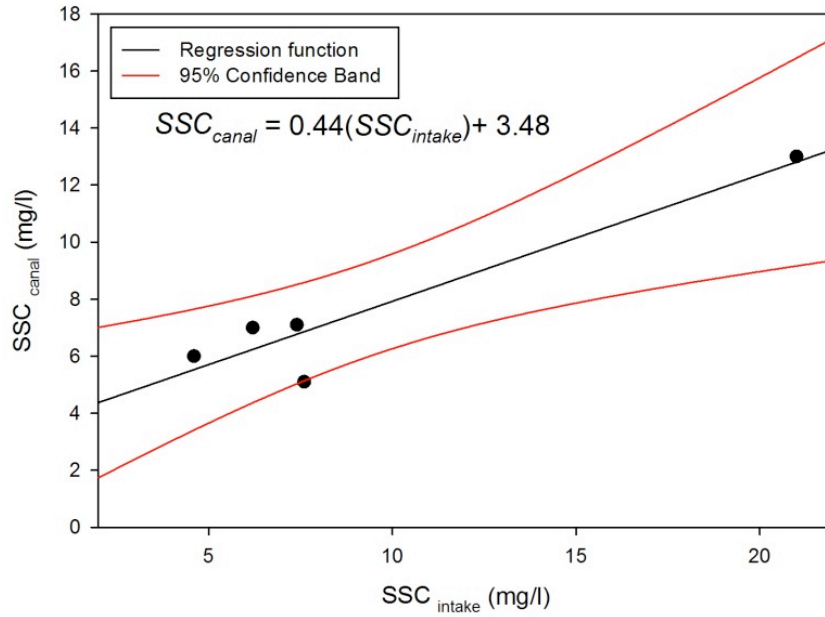


Figure 8: SSC paired samples from sampler intake and canal. Regression function used to estimate SSC bias between samples obtained via the sampler and depth-width averaged samples from the canal.

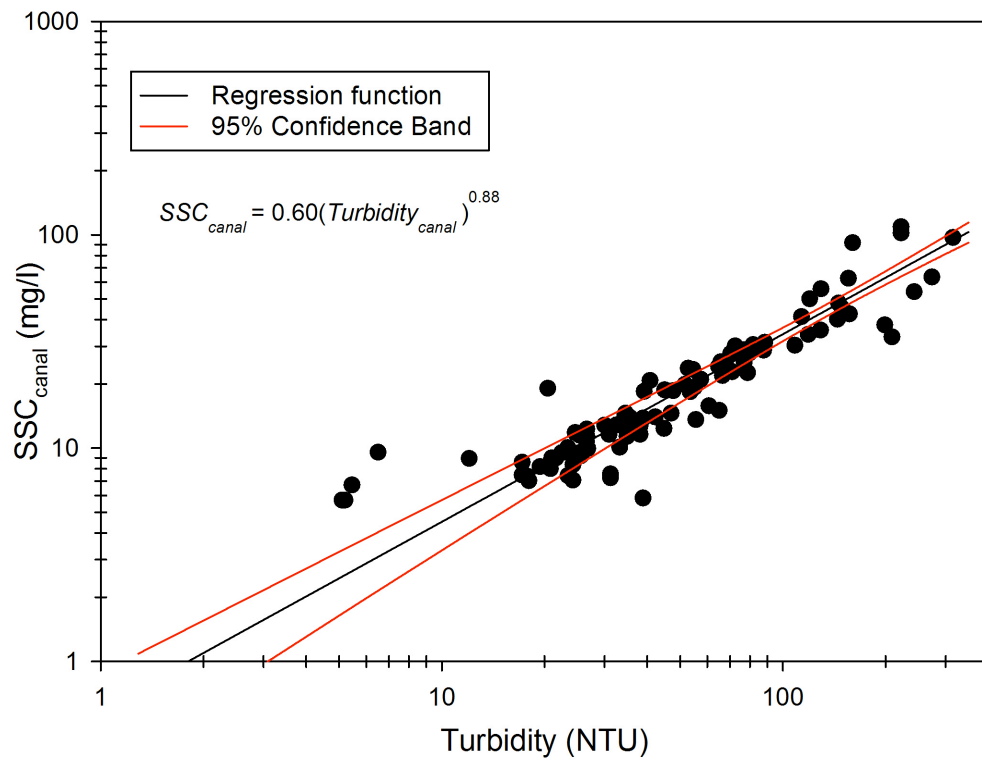


Figure 9. Relationship between SSC corrected to represent depth averaged values, and turbidity readings within the canal for five sampled storm events.

Derivation of suspended sediment concentrations using measured USGS gage data was carried out by Lietz and Debiak (2005). This study was also conducted on a low gradient coastal plains canal, called the C51 Canal in Palm Beach County, FL. Lietz and Debiak (2005) developed a simple linear regression model that was able to explain 85% of the variation of log transformed suspended sediment concentrations with log transformed turbidity as an explanatory variable. A similar linear regression fit to the log transformed values in this study (Figure 10) explained 82% of the variability in the data. Both studies report comparable slopes for the linear regression model; Lietz and Debiak (2005) regression slope is 0.75, and for this study 0.73 (refer Figure 10). The intercept terms from the two studies however are different, Lietz and Debiak (2007) report a intercept term of 0.3, while that derived in this study was only 0.017.

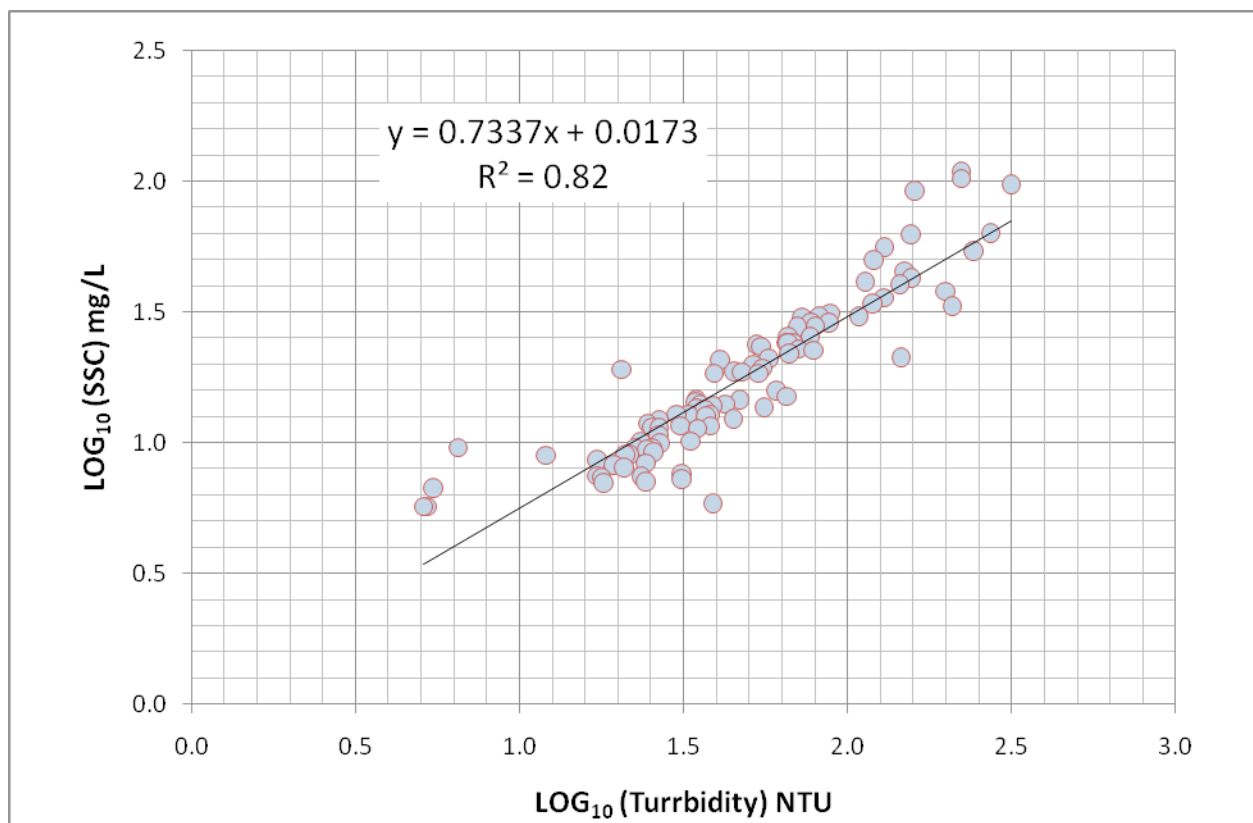


Figure 10: Log transformed suspended sediment concentrations versus the log transformed turbidity values as measured by the USGS gage at Crabtree Canal

The cumulative suspended sediment transported during the period of record (Figure 11) was derived based on measured turbidity data using the relationship defined in Equation 3. The total annual sediment yield for the Crabtree Canal watershed was 1,138 tons, or 380 tons/yr. When normalized by watershed area, the annual sediment yield per unit area of contributing watershed was 19 tons/km<sup>2</sup>/yr.

A study by Simon and Klimetz (2008) that developed annual suspended sediment yields for Southeastern streams instrumented with USGS gages and classified as stable and unstable

streams provides a useful framework for comparison of sediment yields from Crabtree Canal. Simon and Klimetz (2008) suggest that for a stable and unstable stream in the Middle Atlantic Coastal Plain, the median (50<sup>th</sup> percentile) suspended sediment yield is 2.4 tons/km<sup>2</sup>/yr, and 11.1 tons/km<sup>2</sup>/yr respectively. Based on the suspended sediment yield of 19 tons/km<sup>2</sup>/yr calculated from this study, Crabtree Canal falls within the 50<sup>th</sup> to 75<sup>th</sup> percentile range for *unstable* streams based on an analysis of 24 sites on the Middle Atlantic Coastal Plain. The suspended sediment yields calculated by this study corroborate the hypothesis that Crabtree Canal is geomorphically an unstable system.

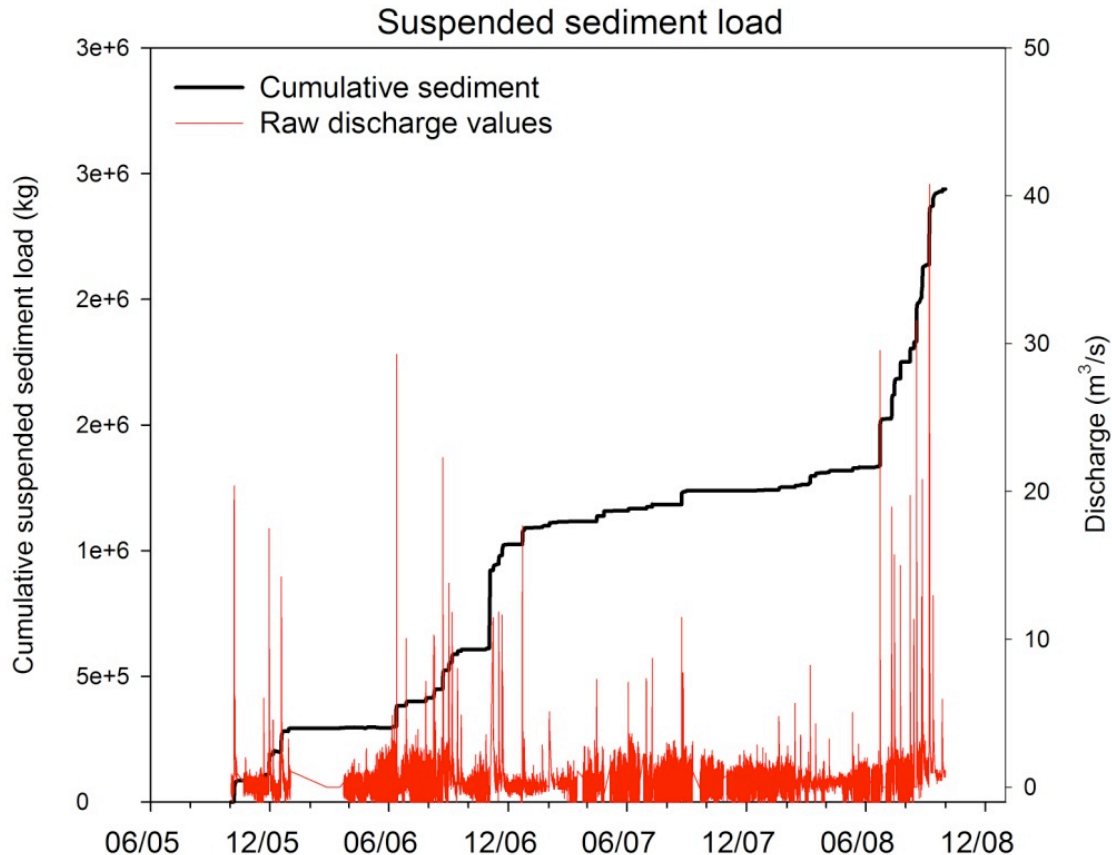


Figure 11: Suspended sediment yield as a function of turbidity and raw discharge data from the tidally influenced USGS gage at Crabtree Canal.

The analysis of the temporal distribution of sediments suggest that continuous turbidity measurements serve as a good surrogate for determining the temporal distribution of suspended sediment concentration in Crabtree Canal. The turbidity data over five years were used to assess the suspended sediment yield from the watershed. The calculated sediment yield from the watershed is relatively high and is an indicator of the instability that can be prevalent in the drainage system.

### ***Spatial distribution of sources that supply sediments to the main stem of Crabtree***

An important aspect of determining the current state of sediments transported through the Crabtree Canal system was determining those tributaries that supply the most sediment. This would serve as a means to identify potential sediment sources, channel instabilities, sites for potential restoration, and a basis for comparisons with 'hot spots' predicted by the hydrodynamic model. To achieve this objective, 16 sites were sampled following 3 storm events and 3 times during dry weather (Table 6). The turbidity and SSC data are summarized in Tables 7 and 8. Correlations of SSC vs turbidity (Figure 12) were observed at most of the sites, these data are summarized in Table 9. The overall correlation of SSC versus turbidity measured during the watershed-wide survey was not as high ( $R^2 = 0.62$ ) when compared to similar measurements made at Long Avenue alone where the coefficient of determination was 80% (Figure 9). The power functions that were fit to both dataset while not identical were similar in value. Coefficients for the power functions fit to the data obtained from five storms at Long Avenue and during the spatial survey were 0.6 and 0.8 respectively; exponents were 0.88 and 0.92.

The mean values of the wet and dry data at each site are plotted in Figures 13 and 14 for turbidity and SSC, respectively. Also shown in these graphs are one standard deviation (SD) around the mean (error bars) and significant differences between the wet weather and dry weather means. The latter were established using a two-sample *t-test* following an *f-test* to determine whether significant differences existed between the variances for each sample set. Significant differences ( $p < 0.05$ ) were observed in the channel along the lower reach from Hwy 501 downstream to Long Avenue. These sites also had the highest wet weather turbidities with all of the means nearly equal to or greater than the SC DHEC WQS of 50 NTU.

Tributaries that also exhibited large wet weather increases in suspended sediments included the Stream by Wiegand Timber on Hwy 501, Altman Branch and Four Mile Road. The Stream by Wiegand Timber on Hwy 501 had the consistently highest wet weather turbidities, followed by Altman Branch. The Stream by Wiegand Timber site is immediately downstream of a large construction site which is the likely reason for high turbidity and SSC measurements that were observed during both wet and dry sampling at this site. Mean wet weather and dry weather turbidity measurements at each sample site was extrapolated to graphically illustrate a reach-wise distribution of mean wet and dry turbidity values in Figures 15 and 16 respectively. These trends all suggest that suspended sediment loadings are highest downstream of Hwy 501 and that sediment sources are erosion from the stream banks or possibly the stream bed. The visual observation of failing stream banks suggests that the failing stream are the primary source of suspended sediment loadings. However, the presence of landscape sources of sediments as evidenced by measurements at the Wiegand Timber site suggests that landscape sources such as new construction sites could be contributing to overall sediment loadings in the system.

Due to a lack of sampling sites in the main channel between West Road and Hwy 501, it is not possible to pinpoint the upstream site of streambank erosion, however there is clear visual evidence of stream bank failure along the main stem reaches of the Canal. As shown in Figure 15 and 16, the observations of high turbidities in the Altman Branch during both wet and dry weather sampling, suggest a major sources are at least this far upstream. However, no flow

measurements were made at the time of sampling hence high sediment concentrations only suggest high sediment *loading* but cannot be known without a simultaneous measure of flow at the sample site.

Table 6. Crabtree watershed-wide surveys: sampling dates and rain accumulations. The latter are the accumulations reported from the rain gage deployed by the USGS at Long Avenue.

| <b>Survey date</b> | <b><i>Antecedent weather conditions</i></b>   |
|--------------------|---|
| 1/15/2008          | Dry for a minimum of 72 hrs prior to sampling   |
| 2/14/2008          | 0.2" precipitation in the 24 hours prior to sampling, and 1.8" precipitation in the 48 hours prior to sampling. |
| 4/30/2008          | Dry for a minimum of 72 hrs prior to sampling   |
| 7/6/2008           | 0.68" precipitation in the 24 hours prior to sampling.  |
| 7/24/2008          | 1.81" precipitation in the 24 hours prior to sampling.  |
| 9/30/2008          | Dry for a minimum of 72 hrs prior to sampling   |

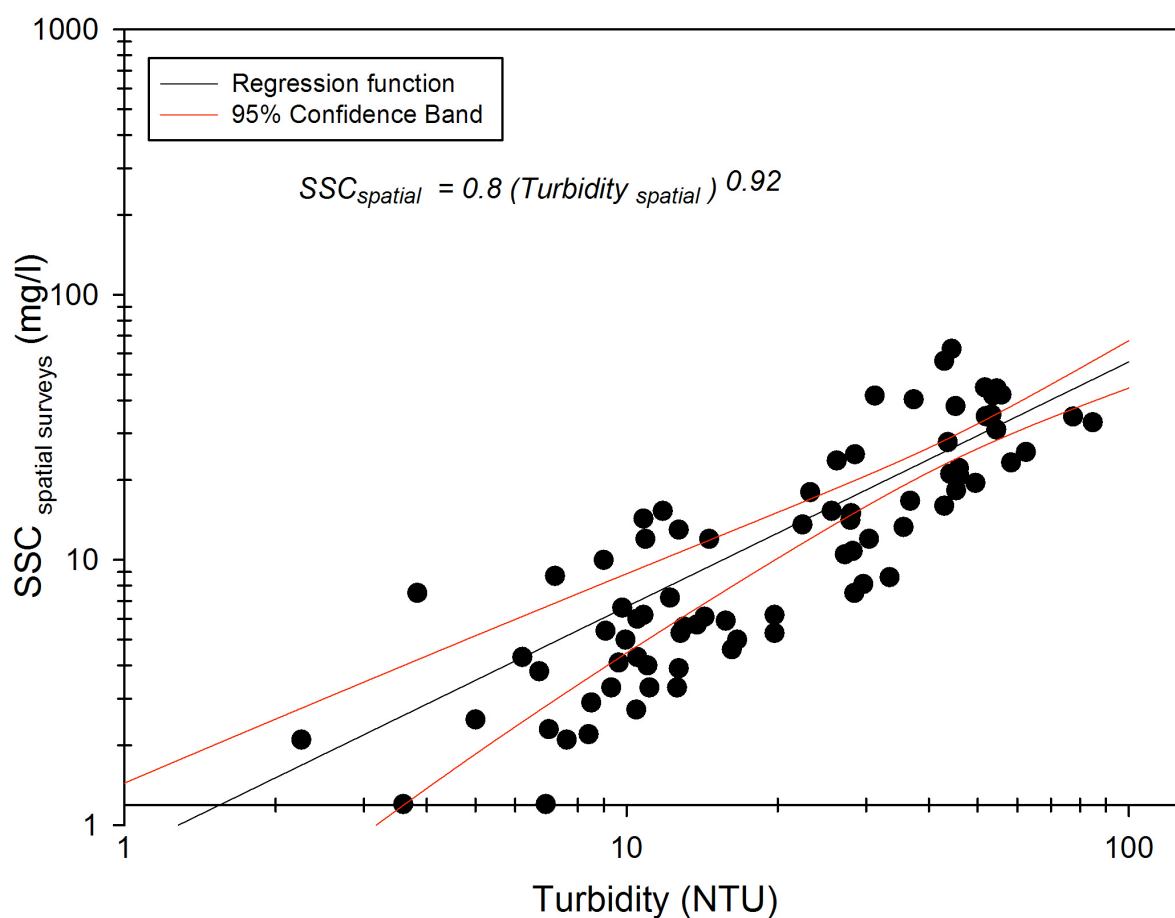


Figure 12. SSC versus turbidity for samples collected during the spatial survey of the Crabtree drainage basin.

Table 7. Turbidity data collected during geographic surveys of the Crabtree Drainage Basin. Main channel locations are in red. All other sites are tributaries.

| Field Site Information |                                     | Turbidity (NTU)      |                     |                      |                                   |         |         |
|------------------------|-------------------------------------|----------------------|---------------------|----------------------|-----------------------------------|---------|---------|
|                        |                                     | Wet Weather Sampling |                     |                      | Dry Weather Sampling <sup>a</sup> |         |         |
| Site ID                | Site Location                       | 2/14/08 <sup>b</sup> | 7/6/08 <sup>c</sup> | 7/24/08 <sup>d</sup> | 1/15/08                           | 4/30/08 | 9/30/08 |
| 17 NC2                 | Ned Creek and Hwy 548               | 16.6                 | 2.25                | 37.3                 | 5.7                               | 10.8    | 10.9    |
| 16 FM                  | Fourmile Rd and Hwy 501             | 27.9                 | 28.5                | 26.2                 | 23.0                              | 22.4    | 14.6    |
| 15 SS                  | Sioux Swamp Drive                   | 27.2                 | 12.2                | <b>51.7</b>          | 6.9                               | 8.5     | 10.5    |
| 14 DS                  | Dunn Shortcut                       | 28.0                 | 7.60                | 42.9                 | 7.1                               | 6.9     | 9.6     |
| 13 OS                  | Oakey Swamp at Dayton Dr            | 33.4                 | 9.32                | <b>53.3</b>          | 8.1                               | 28.4    | 11.1    |
| 12 WR                  | West Rd                             | 30.4                 | 12.8                | 45.2                 | 10.8                              | 19.7    | 10.5    |
| 11 AB                  | Altman Branch                       | 35.6                 | 46.2                | 44.1                 | 6.6                               | 16.2    | 10.0    |
| 10 WT                  | Stream by Wiegand Timber on Hwy 501 | <b>84.8</b>          | 11.8                | <b>77.5</b>          | 15.0                              | 31.2    | 9.1     |
| 8 TG                   | Stream draining Pond on Hwy 501     | 44.4                 | 12.7                | 10.8                 | 21.4                              | dry     | 13.8    |
| 9 P                    | Pond on Hwy 501                     | 6.2                  | 3.8                 | 9.00                 | ND                                | 7.2     | 10.5    |
| 7 MPS                  | Mill Pond Stream                    | 28.2                 | 25.6                | 43.6                 | ND                                | 29.6    | 11.0    |
| 6 H501                 | Hwy 501                             | 42.9                 | <b>54.5</b>         | <b>54.6</b>          | 10.8                              | 19.7    | 13.0    |
| 4 OS                   | Oak Street                          | 45.3                 | 46.0                | <b>53.7</b>          | 10.0                              | 15.8    | 12.7    |
| 3 H701                 | Hwy 701                             | 49.5                 | <b>58.3</b>         | <b>51.9</b>          | 7.9                               | 7.0     | 14.3    |
| 2 LA                   | Long Avenue                         | <b>62.4</b>          | 36.7                | <b>55.8</b>          | 6.1                               | 9.8     | 12.6    |
| 1 CC                   | Country Club Avenue                 | 6.7                  | 3.6                 | 23.2                 | 1.9                               | 8.4     | 5.0     |

**Bold** values exceed SC DHEC Water Quality Standards (i.e., turbidity >50 NTU)

<sup>a</sup> No precipitation for at least 72 hours prior to sampling.

<sup>b</sup> 0.2" precip. in the 24 hours prior to sampling, and 1.8" precip. in the 48 hours prior to sampling.

<sup>c</sup> 0.68" precipitation in the 24 hours prior to sampling.

<sup>d</sup> 1.81" precipitation in the 24 hours prior to sampling.

Table 8. SSC data collected during geographic surveys of the Crabtree Drainage Basin. Main channel locations are in red. All other sites are tributaries.

| Field Site Information |                                    | SSC (mg/L)           |                     |                      |                                   |         |         |
|------------------------|------------------------------------|----------------------|---------------------|----------------------|-----------------------------------|---------|---------|
|                        |                                    | Wet Weather Sampling |                     |                      | Dry Weather Sampling <sup>a</sup> |         |         |
| Site ID                | Site Location                      | 2/14/08 <sup>b</sup> | 7/6/08 <sup>c</sup> | 7/24/08 <sup>d</sup> | 1/15/08                           | 4/30/08 | 9/30/08 |
| 17 NC2                 | Ned Creek and Hwy 548              | 5.0                  | 2.1                 | 40.3                 | NA                                | 14.3    | 12.0    |
| 16 FM                  | Fourmile Rd and Hwy 501            | 14.2                 | 25.0                | 23.7                 | NA                                | 13.6    | 12.0    |
| 15 SS                  | Sioux Swamp Drive                  | 10.5                 | 7.2                 | 44.7                 | NA                                | 2.9     | 4.3     |
| 14 DS                  | Dunn Shortcut                      | 15.0                 | 2.1                 | 56.3                 | NA                                | 1.2     | 4.1     |
| 13 OS                  | Oakey Swamp at Dayton Dr           | 8.6                  | 3.3                 | 35.3                 | NA                                | 7.5     | 3.3     |
| 12 WR                  | West Rd                            | 12.0                 | 5.3                 | 38.0                 | NA                                | 5.3     | 2.7     |
| 11 AB                  | Altman Branch                      | 13.3                 | 22.2                | 21.1                 | NA                                | 4.6     | 5.0     |
| 10 WT                  | Stream by Wiegand Timb. on Hwy 501 | 33.0                 | 15.3                | 34.7                 | NA                                | 41.6    | 5.4     |
| 8 TG                   | Stream draining Pond on Hwy 501    | 4.3                  | 7.5                 | 10.0                 | NA                                | 8.7     | 5.7     |
| 9 P                    | Pond on Hwy 501                    | 62.5                 | 13.0                | 6.2                  | NA                                | NA      | 6.0     |
| 7 MPS                  | Mill Pond Stream                   | 10.8                 | 15.3                | 27.8                 | NA                                | 8.1     | 4.0     |
| 6 H501                 | Hwy 501                            | 16.0                 | 31.0                | 44.3                 | NA                                | 6.2     | 5.6     |
| 4 OS                   | Oak Street                         | 18.3                 | 20.7                | 41.7                 | NA                                | 5.9     | 3.9     |
| 3 H701                 | Hwy 701                            | 19.5                 | 23.3                | 34.8                 | NA                                | 2.3     | 6.1     |
| 2 LA                   | Long Avenue                        | 25.5                 | 16.7                | 42.0                 | NA                                | 6.6     | 3.3     |
| 1 CC                   | Country Club Avenue                | 3.8                  | 1.2                 | 18.0                 | NA                                | 2.2     | 2.5     |

**Bold** values exceed Water Quality Standards (i.e., DO <4 ppm, pH <6 or >8.5, turbidity >50 NTU)

<sup>a</sup> No precipitation for at least 72 hours prior to sampling.

<sup>b</sup> 0.2" precip. in the 24 hours prior to sampling, and 1.8" precip. in the 48 hours prior to sampling.

<sup>c</sup> 0.68" precipitation in the 24 hours prior to sampling.

<sup>d</sup> 1.81" precipitation in the 24 hours prior to sampling.

Table 9. Correlations at each survey site for SSC vs turbidity (n=5).

| <i>Site name</i> | <i>Site name</i>                    | <i>SSC vs Turb</i> |
|------------------|-------------------------------------|--------------------|
| 17               | Ned Creek and Hwy 548               | 0.83               |
| 16               | Fourmile Rd and Hwy 501             | 0.43               |
| 15               | Sioux Swamp Drive                   | 0.93               |
| 14               | Dunn Shortcut                       | 0.89               |
| 13               | Oakey Swamp at Dayton Dr            | 0.82               |
| 12               | West Rd                             | 0.88               |
| 11               | Altman Branch                       | 0.95               |
| 10               | Stream by Wiegand Timber on Hwy 501 | 0.44               |
| 9                | Stream draining Pond on Hwy 501     | 0.01               |
| 8                | Pond on Hwy 501                     | 1.00               |
| 7                | Mill Pond Stream                    | 0.76               |
| 6                | Hwy 501                             | 0.81               |
| 4                | Oak Street                          | 0.79               |
| 3                | Hwy 701                             | 0.80               |
| 2                | Long Avenue                         | 0.77               |
| 1                | Country Club Avenue                 | 0.96               |

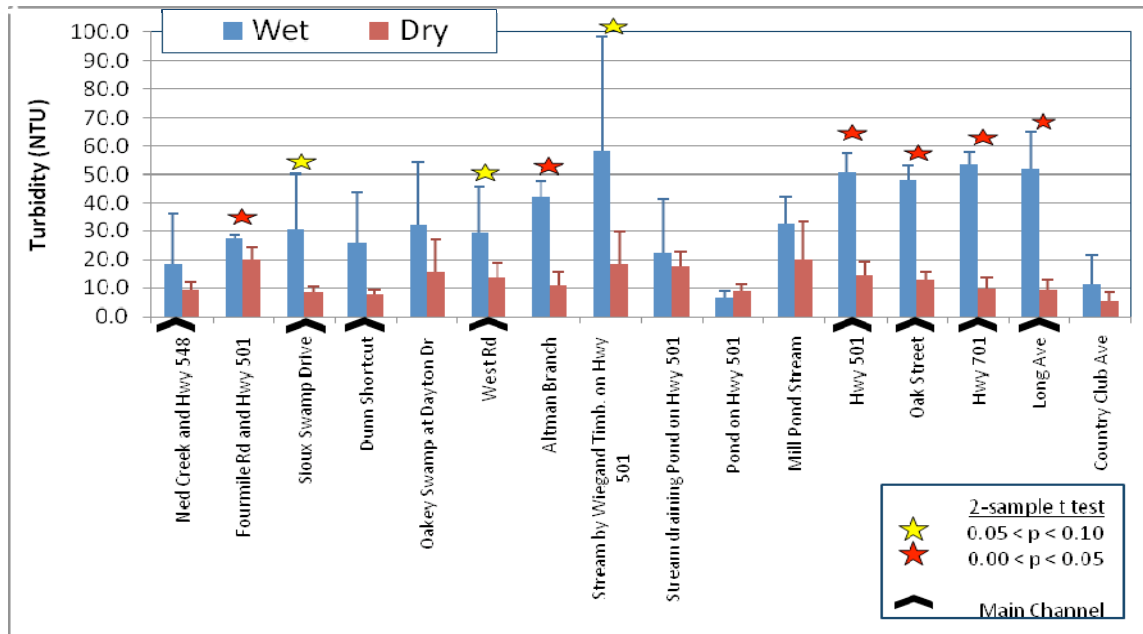


Figure 13. Wet and Dry means ( $n = 3$  each) for the turbidity at each site sampled in the Crabtree drainage basin. The error bars represent 1 SD around the mean. A two-sample t test was used to determine a one-tailed p value to provide a measure of the significance of higher wet weather means.

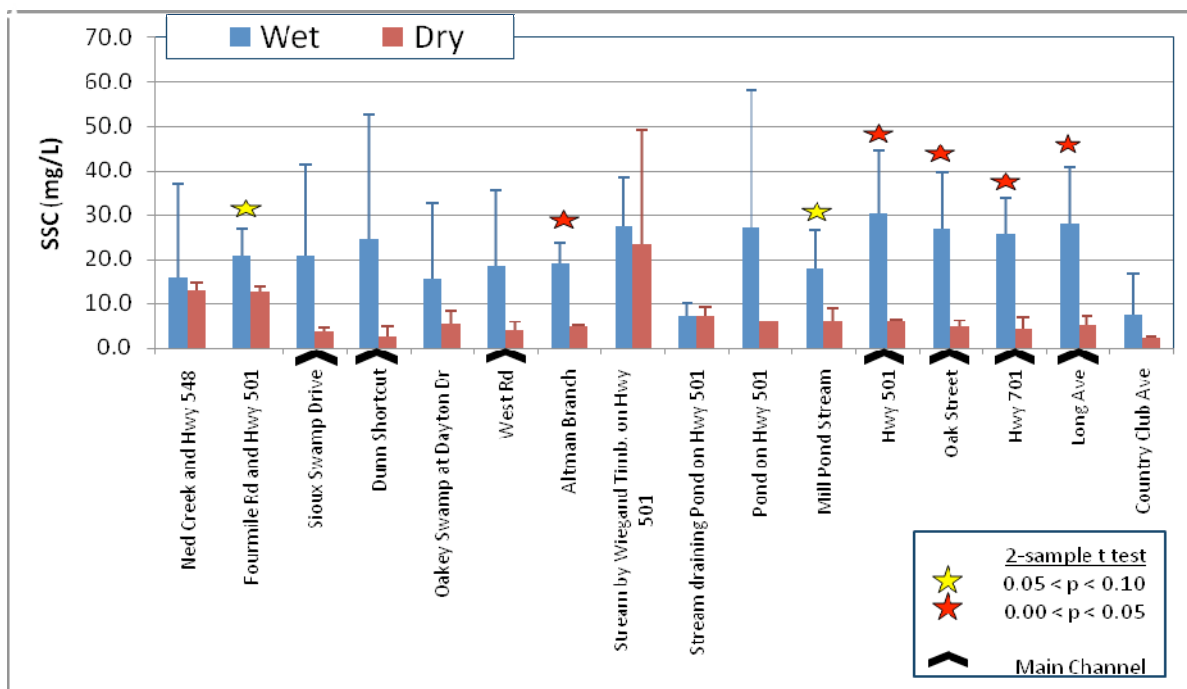


Figure 14. Wet and Dry means ( $n = 3$  each) for the SSC concentration at each site sampled in the Crabtree drainage basin. The error bars represent 1 SD around the mean. A two-sample t test was used to determine a one-tailed p value to provide a measure of the significance of higher wet weather means.

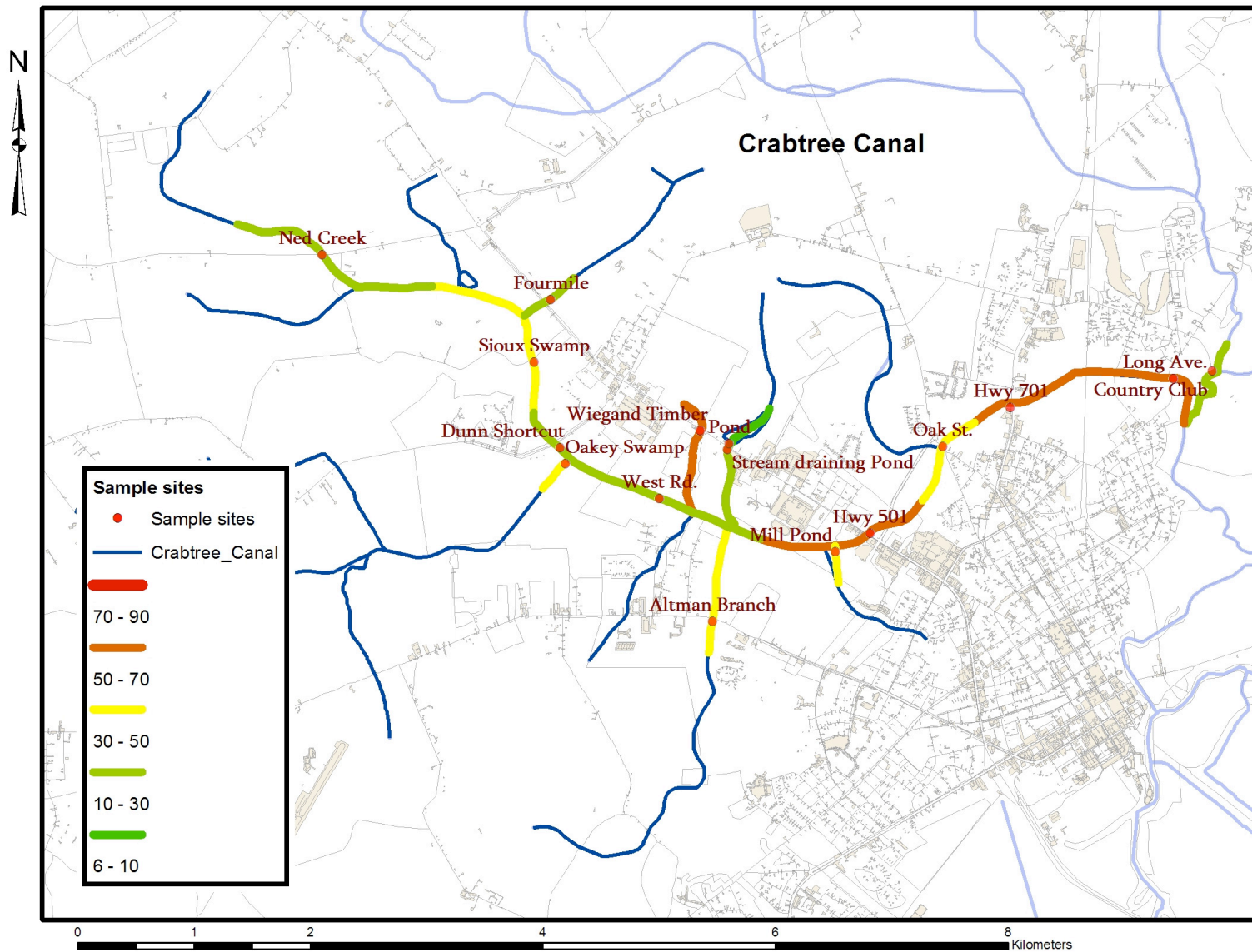


Figure 15. Mean value based on three wet weather samples taken at sample sites in the Crabtree watershed.

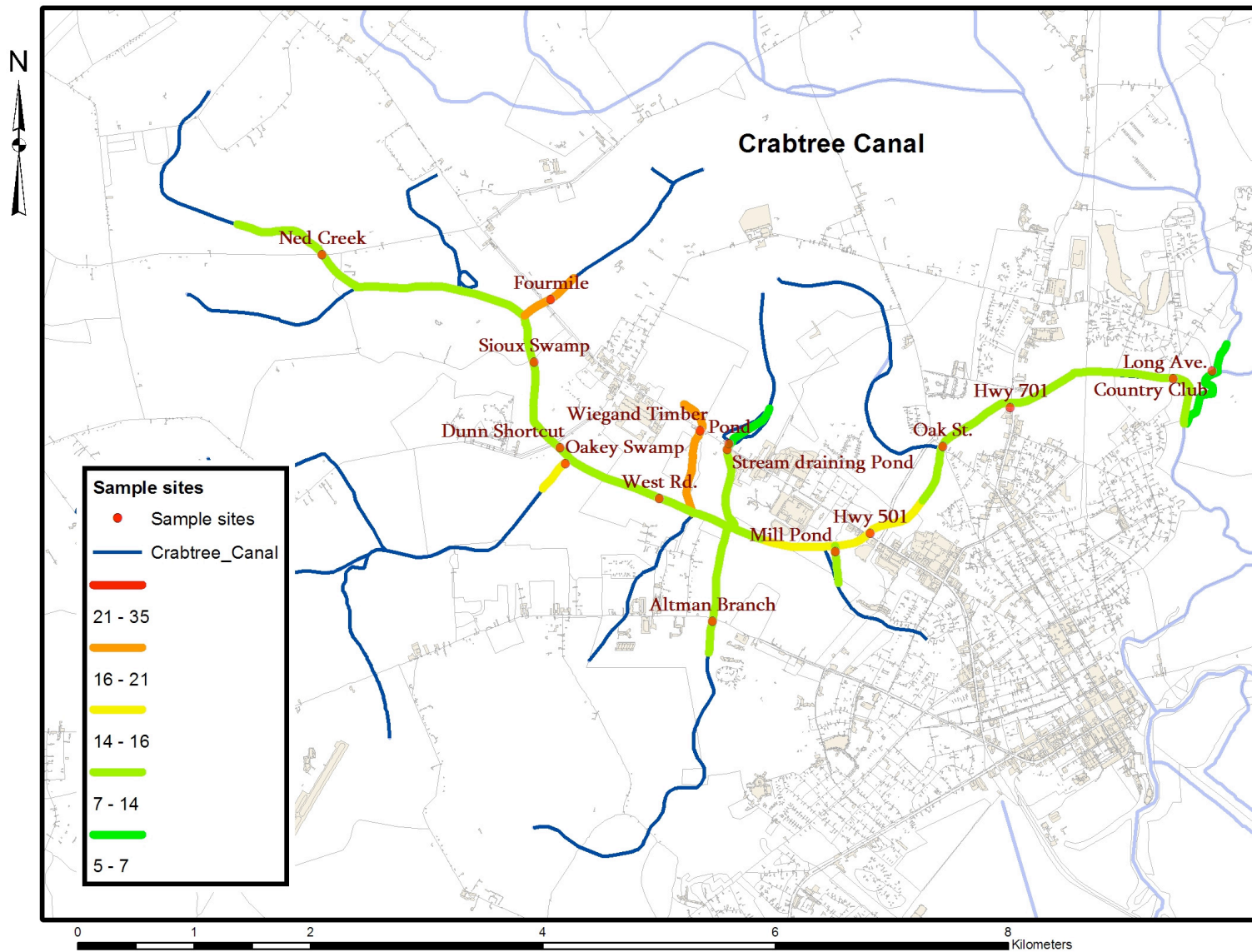


Figure 16. Mean value based on three wet weather samples taken at sample sites in the Crabtree watershed.

## ***Sediment contributions to organic loadings in the Crabtree Canal***

### ***Impact of Sediments on Dissolved Oxygen Deficits***

The Long Avenue site at Crabtree Canal is currently 303(d) listed for dissolved oxygen and has been since 1998. Sources of oxygen demand include: (1) dissolved natural organic matter, including colored humic materials, (2) dissolved organics of anthropogenic origin, (3) particulate organics of anthropogenic origin include septage and soils, and (4) ammonium. An estimate of the total oxygen demand in the water is provided by the 5-day BOD<sub>5</sub> (EPA Method 405.1). This operational test is performed on unfiltered water. To evaluate the role of sediments in the load of oxygen-demanding materials, a regression analysis was performed for SSC versus BOD<sub>5</sub> (Figure 17) and VSS versus BOD<sub>5</sub> (Figure 18). The poor correlations suggest that most of the BOD<sub>5</sub> is associated with dissolved organic matter and ammonium.

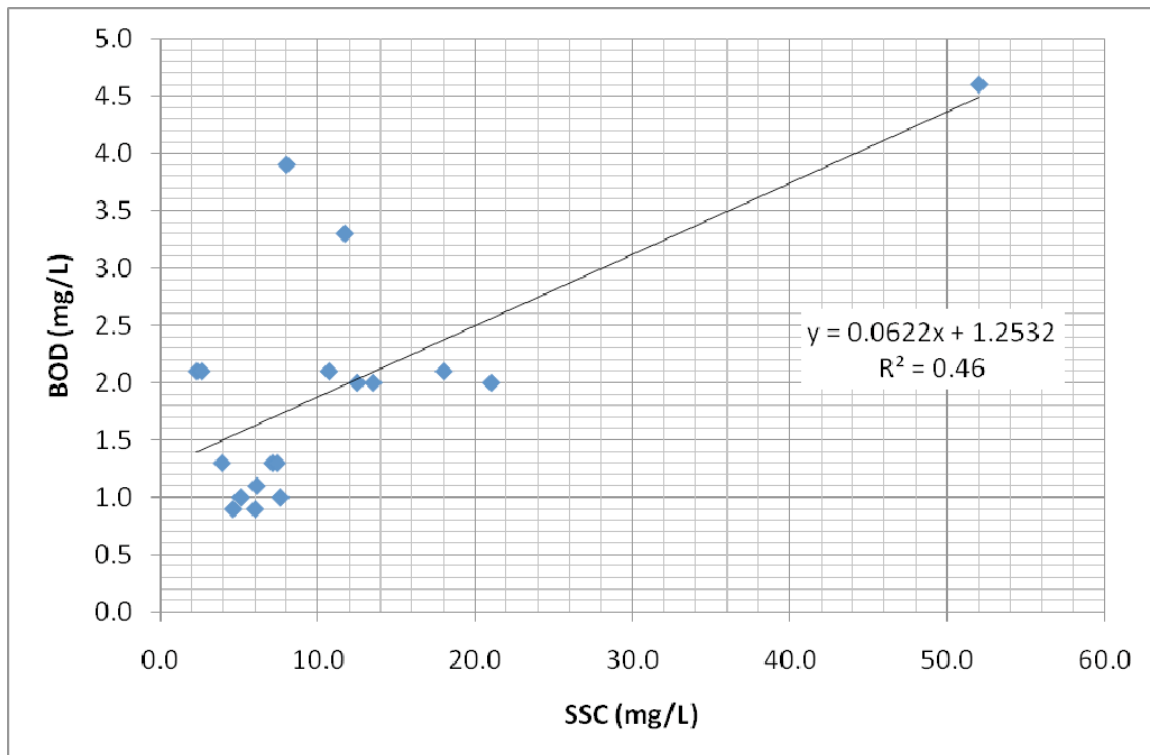


Figure 17. BOD<sub>5</sub> versus SSC in the biweekly depth-integrated samples collected from Crabtree Canal at Long Avenue. BOD errors are approximately as large as the sample symbols.

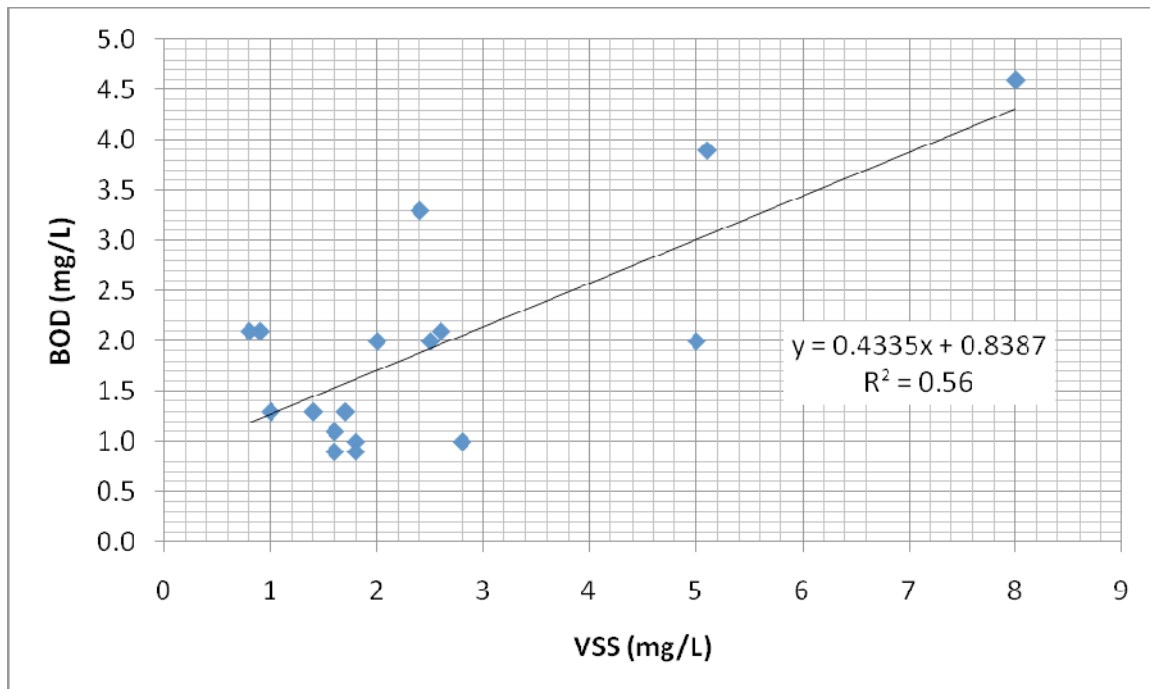


Figure 18. BOD<sub>5</sub> versus VSS in the biweekly depth-integrated samples collected from Crabtree Canal at Long Avenue. BOD errors are approximately as large as the sample symbols.

#### *Particle Composition*

Regression analysis of SSC versus VSS was used to characterize the variability in organic content of the suspended sediments. As shown in Figure 19, the autosampler collected samples that exhibited an excellent correlation of VSS with SSC. A similar relationship was found in the biweekly depth-integrated grab samples as shown in Figure 20. In both datasets, the slope of the line is 0.14, i.e., a %VSS of 14%. This is relatively low for a swamp environment suggesting the lack of connectivity between the legacy floodplains and the main channel. This lack of connectivity could be caused by the barrier created by the dredge spoils which have formed a levee on the banks of the channel.

The SSC versus VSS correlation derived from measurements taken across the watershed is shown in Figure 21. It is also not as good as at Long Avenue ( $R^2 = 0.73$ ) and has a slightly higher slope (0.20), suggesting a suspended load comprising of higher organic content for a given SSC. The similarity in particle composition among the dry and wet weather samples suggests similar source areas. At all but the most upstream site, %VSS was lower during wet weather as compared to dry, but the differences were not significant. Figures 22 and 23 shows the correlation of %VSS with SSC in samples collected via the autosampler and during the spatial surveys respectively. It is notable that the highest %VSS values are observed at low SSC concentrations both at the watershed outlet (Long Avenue) and when measured at various points in the watershed. A 3-parameter exponential decay function was fit to the data; this function explained 64% of the variability in %VSS with SSC for samples collected at Long Avenue (Figure

22) and only 18% of the variability in the data collected during the spatial survey throughout the watershed (Figure 23). Collectively, these patterns are consistent with a more organic enriched particle source at head of the drainage basin and a more organic depleted source at the terminus (Long Avenue). This is likely reflecting dilution by a higher load of inorganic detrital particles along the lower reaches of the canal.

Table 10. Correlations at each survey site for SSC versus VSS (n = 5).

| <i>Site name</i> | <i>Site name</i>                    | <i>SSC vs VSS</i> |
|------------------|-------------------------------------|-------------------|
| 17               | Ned Creek and Hwy 548               | 0.99              |
| 16               | Fourmile Rd and Hwy 501             | 0.99              |
| 15               | Sioux Swamp Drive                   | 1.00              |
| 14               | Dunn Shortcut                       | 1.00              |
| 13               | Oakey Swamp at Dayton Dr            | 0.97              |
| 12               | West Rd                             | 0.98              |
| 11               | Altman Branch                       | 0.99              |
| 10               | Stream by Wiegand Timber on Hwy 501 | 0.99              |
| 9                | Stream draining Pond on Hwy 501     | 0.74              |
| 8                | Pond on Hwy 501                     | 1.00              |
| 7                | Mill Pond Stream                    | 0.96              |
| 6                | Hwy 501                             | 0.93              |
| 4                | Oak Street                          | 0.95              |
| 3                | Hwy 701                             | 0.96              |
| 2                | Long Avenue                         | 0.94              |
| 1                | Country Club Avenue                 | 0.98              |

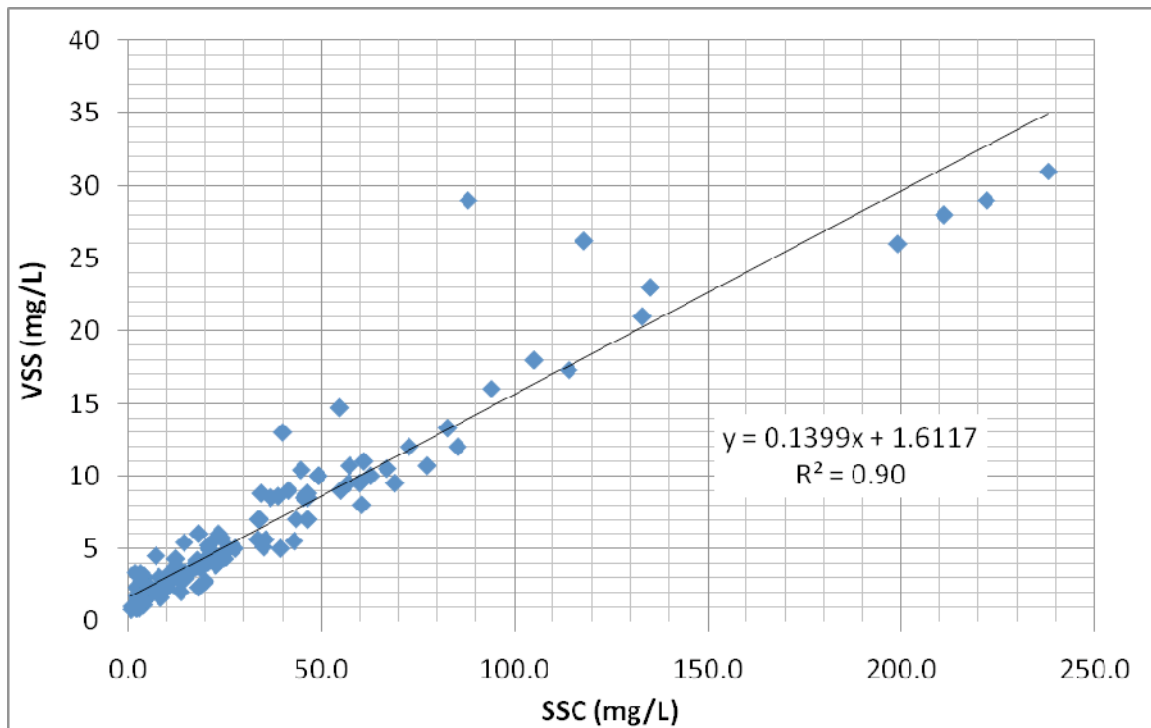


Figure 19. VSS versus SSC in samples collected during storm events via autosampler at Long Avenue.

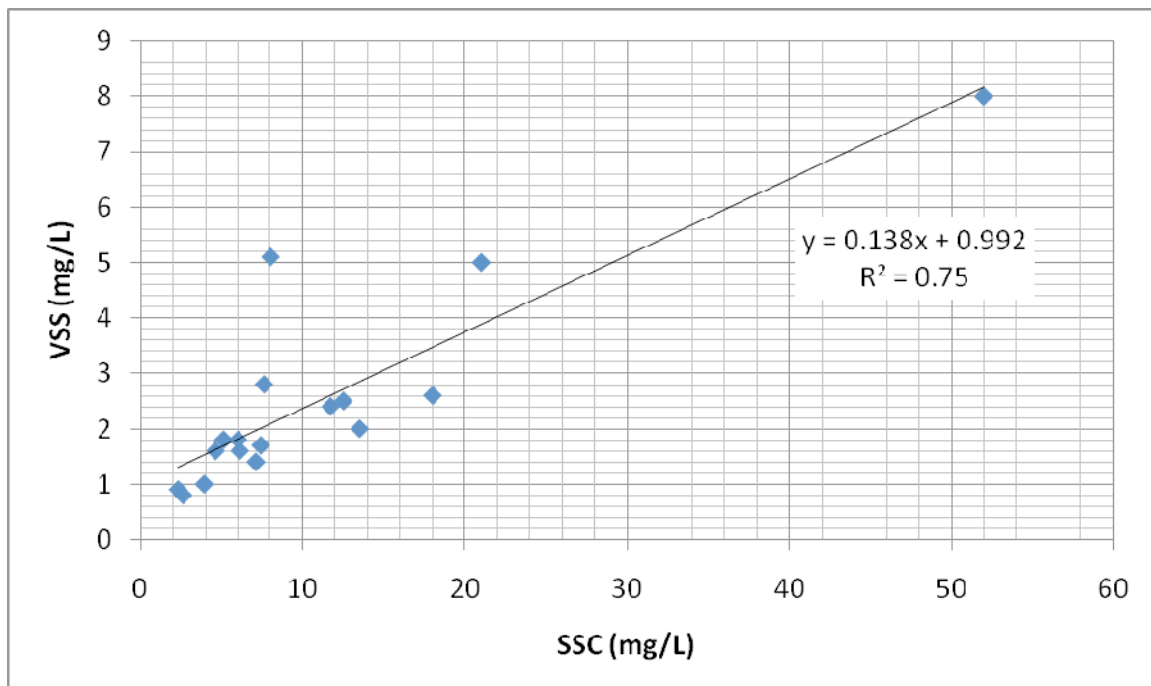


Figure 20. VSS versus SSC in depth-integrated samples collected biweekly midstream at Long Avenue.

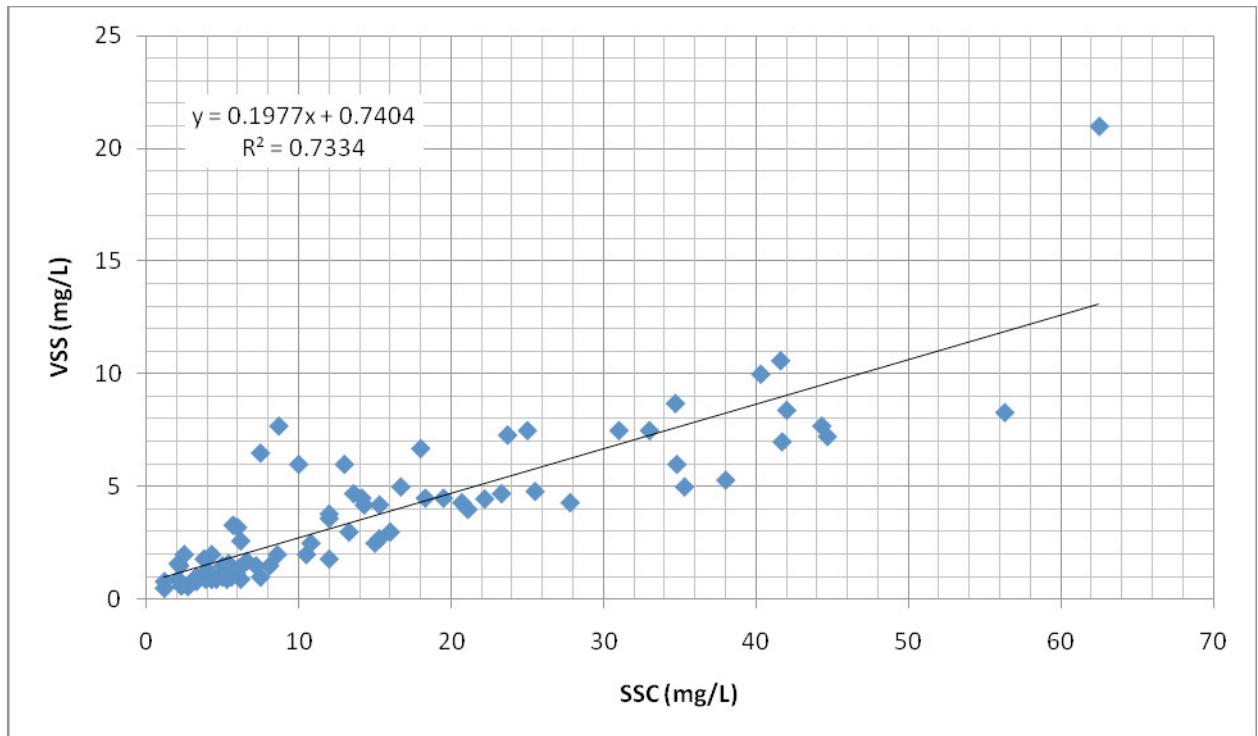


Figure 21. SSC versus VSS in the samples collected during the spatial surveys of the Crabtree drainage basin.

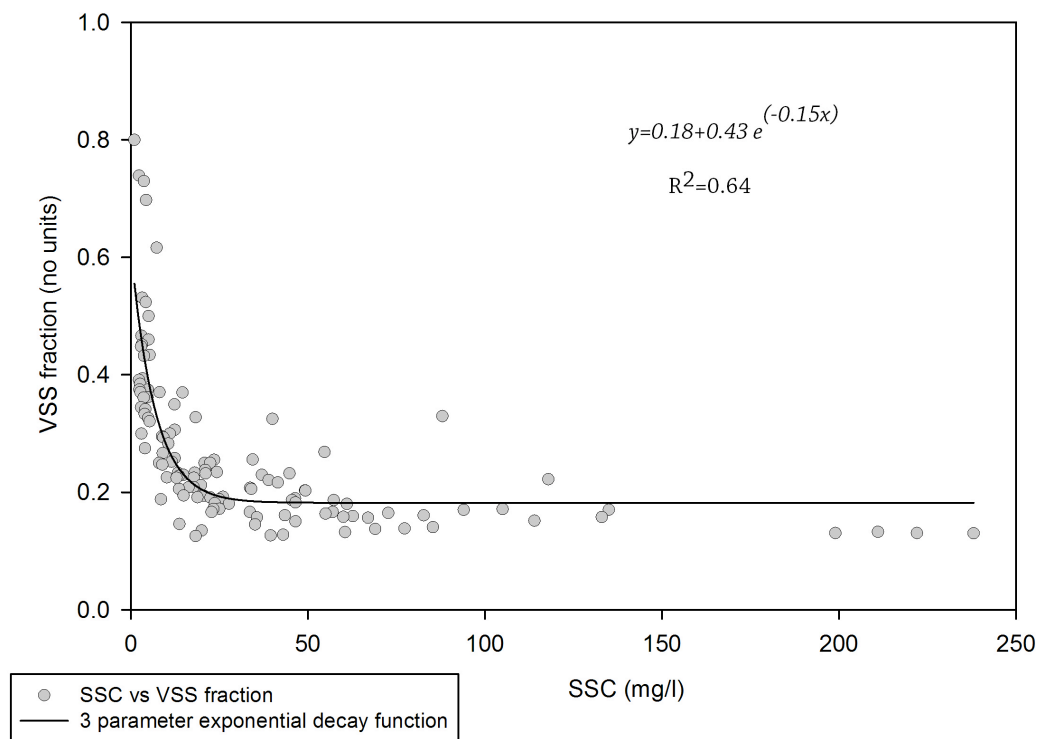


Figure 22. %VSS versus SSC in the samples collected through the autosampler during five storm events at Long Avenue.

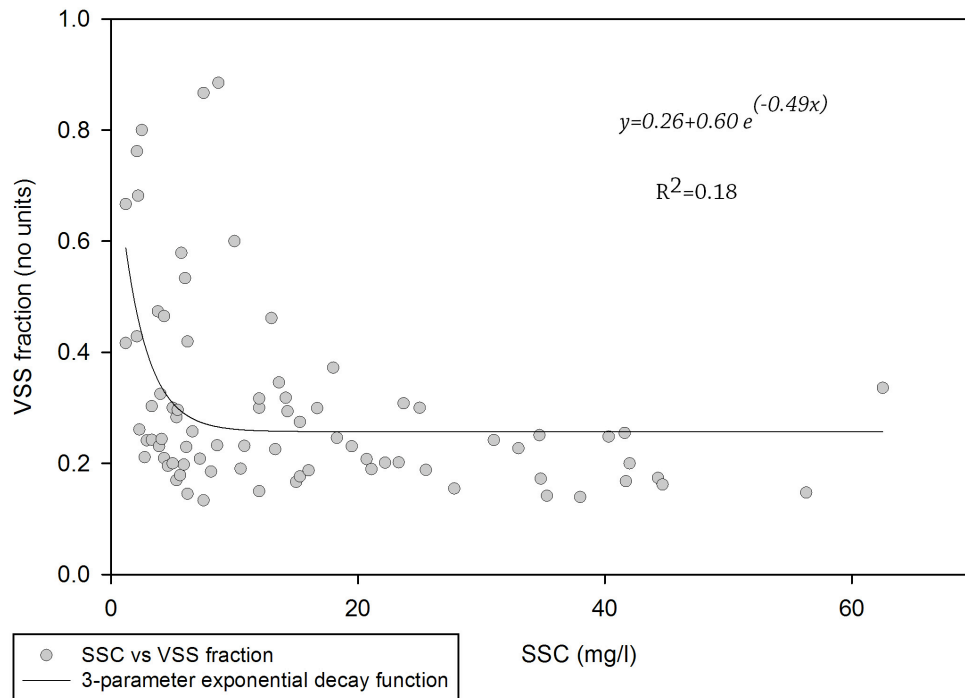


Figure 23. %VSS versus SSC in the samples collected during the spatial surveys of the Crabtree drainage basin.

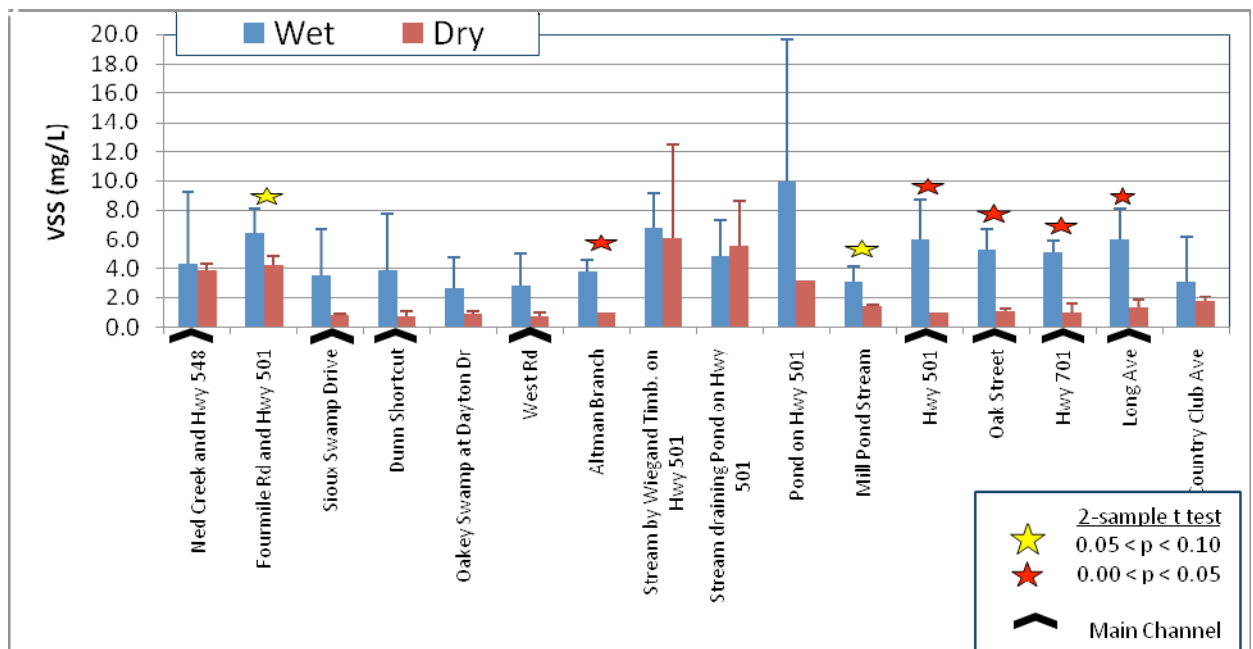


Figure 24. Wet and Dry means ( $n = 3$  each) for the VSS concentration at each site sampled in the Crabtree drainage basin. The error bars represent 1 SD around the mean. A two-sample t test was used to determine a one-tailed p value to provide a measure of the significance of higher wet weather means.

Table 11. VSS data collected during geographic surveys of the Crabtree Drainage Basin. Main channel locations are in red. All other sites are tributaries.

| Field Site Information |                                    | VSS (mg/L)           |                     |                      |                                   |         |         |
|------------------------|------------------------------------|----------------------|---------------------|----------------------|-----------------------------------|---------|---------|
|                        |                                    | Wet Weather Sampling |                     |                      | Dry Weather Sampling <sup>a</sup> |         |         |
| Site ID                | Site Location                      | 2/14/08 <sup>b</sup> | 7/6/08 <sup>c</sup> | 7/24/08 <sup>d</sup> | 1/15/08                           | 4/30/08 | 9/30/08 |
| 17 NC2                 | Ned Creek and Hwy 548              | 1.5                  | 1.6                 | 10.0                 | NA                                | 4.2     | 3.6     |
| 16 FM                  | Fourmile Rd and Hwy 501            | 4.5                  | 7.5                 | 7.3                  | NA                                | 4.7     | 3.8     |
| 15 SS                  | Sioux Swamp Drive                  | 2.0                  | 1.5                 | 7.2                  | NA                                | 0.7     | 0.9     |
| 14 DS                  | Dunn Shortcut                      | 2.5                  | 0.9                 | 8.3                  | NA                                | 0.5     | 1.0     |
| 13 OS                  | Oakey Swamp at Dayton Dr           | 2.0                  | 1.0                 | 5.0                  | NA                                | 1.0     | 0.8     |
| 12 WR                  | West Rd                            | 1.8                  | 1.5                 | 5.3                  | NA                                | 0.9     | 0.6     |
| 11 AB                  | Altman Branch                      | 3.0                  | 4.5                 | 4.0                  | NA                                | 0.9     | 1.0     |
| 10 WT                  | Stream by Wiegand Timb. on Hwy 501 | 7.5                  | 4.2                 | 8.7                  | NA                                | 10.6    | 1.6     |
| 8 TG                   | Stream draining Pond on Hwy 501    | 2.0                  | 6.5                 | 6.0                  | NA                                | 7.7     | 3.3     |
| 9 P                    | Pond on Hwy 501                    | 21.0                 | 6.0                 | 2.6                  | NA                                | NA      | 3.2     |
| 7 MPS                  | Mill Pond Stream                   | 2.5                  | 2.7                 | 4.3                  | NA                                | 1.5     | 1.3     |
| 6 H501                 | Hwy 501                            | 3.0                  | 7.5                 | 7.7                  | NA                                | 0.9     | 1.0     |
| 4 OS                   | Oak Street                         | 4.5                  | 4.3                 | 7.0                  | NA                                | 1.2     | 0.9     |
| 3 H701                 | Hwy 701                            | 4.5                  | 4.7                 | 6.0                  | NA                                | 0.6     | 1.4     |
| 2 LA                   | Long Avenue                        | 4.8                  | 5.0                 | 8.4                  | NA                                | 1.7     | 1.0     |
| 1 CC                   | Country Club Avenue                | 1.8                  | 0.8                 | 6.7                  | NA                                | 1.5     | 2.0     |

**Bold** values exceed Water Quality Standards (i.e., DO <4 ppm, pH <6 or >8.5, turbidity >50 NTU)

<sup>a</sup> No precipitation for at least 72 hours prior to sampling.

<sup>b</sup> 0.2" precip. in the 24 hours prior to sampling, and 1.8" precip. in the 48 hours prior to sampling.

<sup>c</sup> 0.68" precipitation in the 24 hours prior to sampling.

<sup>d</sup> 1.81" precipitation in the 24 hours prior to sampling.

Table 12. %VSS data collected during geographic surveys of the Crabtree Drainage Basin. Main channel locations are in red. All other sites are tributaries.

| Field Site Information  |                                    | Wet Weather Sampling |                     |                      | Dry Weather Sampling <sup>a</sup> |         |         |
|---|------------------------------------|----------------------|---------------------|----------------------|-----------------------------------|---------|---------|
| Site ID   | Site Location                      | 2/14/08 <sup>b</sup> | 7/6/08 <sup>c</sup> | 7/24/08 <sup>d</sup> | 1/15/08                           | 4/30/08 | 9/30/08 |
| 17 NC2  | Ned Creek and Hwy 548              | 30%                  | 76%                 | 25%                  | NA                                | 29%     | 30%     |
| 16 FM   | Fourmile Rd and Hwy 501            | 32%                  | 30%                 | 31%                  | NA                                | 35%     | 32%     |
| 15 SS   | Sioux Swamp Drive                  | 19%                  | 21%                 | 16%                  | NA                                | 24%     | 21%     |
| 14 DS   | Dunn Shortcut                      | 17%                  | 43%                 | 15%                  | NA                                | 42%     | 24%     |
| 13 OS   | Oakey Swamp at Dayton Dr           | 23%                  | 30%                 | 14%                  | NA                                | 13%     | 24%     |
| 12 WR   | West Rd                            | 15%                  | 28%                 | 14%                  | NA                                | 17%     | 21%     |
| 11 AB   | Altman Branch                      | 23%                  | 20%                 | 19%                  | NA                                | 20%     | 20%     |
| 10 WT   | Stream by Wiegand Timb. on Hwy 501 | 23%                  | 27%                 | 25%                  | NA                                | 25%     | 30%     |
| 8 TG  | Stream draining Pond on Hwy 501    | 47%                  | 87%                 | 60%                  | NA                                | 89%     | 58%     |
| 9 P   | Pond on Hwy 501                    | 34%                  | 46%                 | 42%                  | NA                                | NA      | 53%     |
| 7 MPS   | Mill Pond Stream                   | 23%                  | 18%                 | 15%                  | NA                                | 19%     | 33%     |
| 6 H501  | Hwy 501                            | 19%                  | 24%                 | 17%                  | NA                                | 15%     | 18%     |
| 4 OS  | Oak Street                         | 25%                  | 21%                 | 17%                  | NA                                | 20%     | 23%     |
| 3 H701  | Hwy 701                            | 23%                  | 20%                 | 17%                  | NA                                | 26%     | 23%     |
| 2 LA  | Long Avenue                        | 19%                  | 30%                 | 20%                  | NA                                | 26%     | 30%     |
| 1 CC  | Country Club Avenue                | 47%                  | 67%                 | 37%                  | NA                                | 68%     | 80%     |
| <b>Bold</b> values exceed Water Quality Standards (i.e., DO <4 ppm, pH <6 or >8.5, turbidity >50 NTU)<br><sup>a</sup> No precipitation for at least 72 hours prior to sampling.<br><sup>b</sup> 0.2" precip. in the 24 hours prior to sampling, and 1.8" precip. in the 48 hours prior to sampling.<br><sup>c</sup> 0.68" precipitation in the 24 hours prior to sampling.<br><sup>d</sup> 1.81" precipitation in the 24 hours prior to sampling. |                                    |                      |                     |                      |                                   |         |         |

### *Fecal Coliforms*

The Long Avenue and Hwy 501 sampling sites have been 303(d) listed by SC DHEC for fecal coliform impairments. The initial listing for the Long Avenue site was 1998. This site was delisted in 2008 based on sparse data which included a period of historic drought. During the project period, fecal coliform concentrations were collected during the spatial surveys and biweekly sampling at Long Avenue. The former are listed in Table 10 and the latter in Table 3 in concentration units of CFU/100 mL where CFU = colony forming units. Many samples exceeded the detection range and are so designated by a “≥” symbol. The SC DHEC single sample WQS for fecal coliforms in Class FW streams is 400 CFU/100 mL. The wet weather samples have a high prevalence of WQS

contraventions. Mill Pond stream is particularly notable for having contraventions during all of the wet and dry periods sampled.

Table 13. Fecal Coliform data collected during geographic surveys of the Crabtree Drainage Basin. Main channel locations are in red. All other sites are tributaries.

| Field Site Information |                                    | Fecal coliform (MPN/100 mL) |                     |                      |                                   |         |         |
|------------------------|------------------------------------|-----------------------------|---------------------|----------------------|-----------------------------------|---------|---------|
|                        |                                    | Wet Weather Sampling        |                     |                      | Dry Weather Sampling <sup>a</sup> |         |         |
| Site ID                | Site Location                      | 2/14/08 <sup>b</sup>        | 7/6/08 <sup>c</sup> | 7/24/08 <sup>d</sup> | 1/15/08                           | 4/30/08 | 9/30/08 |
| 17 NC2                 | Ned Creek and Hwy 548              | ND                          | 240                 | ≥1600                | ND                                | 300     | 500     |
| 16 FM                  | Fourmile Rd and Hwy 501            | ND                          | 900                 | 500                  | ND                                | 130     | 140     |
| 15 SS                  | Sioux Swamp Drive                  | ND                          | 1600                | 9000                 | ND                                | 50      | 130     |
| 14 DS                  | Dunn Shortcut                      | ND                          | 170                 | ≥1600                | ND                                | 8       | 170     |
| 13 OS                  | Oakey Swamp at Dayton Dr           | ND                          | 13                  | ≥1600                | ND                                | 2       | 30      |
| 12 WR                  | West Rd                            | ND                          | 170                 | ≥1600                | ND                                | 130     | 40      |
| 11 AB                  | Altman Branch                      | ND                          | 1650                | 3000                 | ND                                | 1600    | 80      |
| 10 WT                  | Stream by Wiegand Timb. on Hwy 501 | ND                          | 300                 | ≥1600                | ND                                | 22      | 30      |
| 8 TG                   | Stream draining Pond on Hwy 501    | ND                          | 30                  | 300                  | ND                                |         | 2       |
| 9 P                    | Pond on Hwy 501                    | ND                          | 4                   | 17                   | ND                                | 2       | 4       |
| 7 MPS                  | Mill Pond Stream                   | ND                          | 900                 | 1600                 | ND                                | >1600   | ≥1600   |
| 6 H501                 | Hwy 501                            | ND                          | 900                 | ≥1600                | ND                                | 170     | 300     |
| 4 OS                   | Oak Street                         | ND                          | 300                 | ≥1600                | ND                                | 50      | 500     |
| 3 H701                 | Hwy 701                            | ND                          | 500                 | ≥1600                | ND                                | 70      | 500     |
| 2 LA                   | Long Avenue                        | ND                          | 900                 | ≥1600                | ND                                | 70      | 50      |
| 1 CC                   | Country Club Avenue                | ND                          | 80                  | 500                  | ND                                | 130     | 1600    |

**Bold** values exceed Water Quality Standards (i.e., Fecal Coliform >400 CFU/100 mL)

<sup>a</sup> No precipitation for at least 72 hours prior to sampling.

<sup>b</sup> 0.2" precip. in the 24 hours prior to sampling, and 1.8" precip. in the 48 hours prior to sampling.

<sup>c</sup> 0.68" precipitation in the 24 hours prior to sampling.

<sup>d</sup> 1.81" precipitation in the 24 hours prior to sampling.

### *Uncertainty associated with methods used in this study*

Results from field duplicates are shown in Table 14. These samples were collected on 1/31/08 and 7/16/08 midstream from the bridge at Long Avenue using a depth-integrated sampler. They provide an estimate of the combined uncertainty resulting from the analytical method and natural variability over short time and space scales. The percentage difference in SSC concentration was approximately 10% and for VSS concentration, approximately 17%. Note that the VSS concentrations are much lower than those of the SSC. On 7/16/08, an autosampler grab sample was collected at approximately the same time as the field duplicates from the bridge. The SSC collected by the autosampler was 47% greater than the mean of the bridge grab samples. The VSS was 76% greater.

Table 14: Field duplicates for SSC and VSS collected using a depth integrated sampler from the bridge at Long Avenue.

|                         | <i>1/31/2008</i> |     |            | <i>7/16/2008</i> |      |      |            |             |            |
|-------------------------|------------------|-----|------------|------------------|------|------|------------|-------------|------------|
| <b>Field Duplicates</b> | 1                | 2   | Difference | 1                | 2    | Mean | Difference | Autosampler | Difference |
| SSC (mg/L)              | 2.3              | 2.6 | -12%       | 13.5             | 12.5 | 13.0 | 8%         | 21.0        | -47%       |
| VSS (mg/L)              | 0.9              | 0.8 | 12%        | 2.0              | 2.5  | 2.25 | -22%       | 5.0         | -76%       |

A significant difference ( $p < 0.05$ ) between the SSC and VSS collected via the autosampler as compared to the depth-integrated samples from the bridge was also observed four other dates as shown in Table 15. This significance was established using the Wilcoxon Signed-Ranks Test. In summary, the autosampler collected samples that were on average 10% higher in SSC and 25% higher in VSS. The organic matter content of the SSC expressed as %VSS ( $= \text{VSS}/\text{SSC} \times 100$ ) was therefore 4% higher in the samples collected by the autosampler as compared to the depth-integrated samples from the bridge.

The significant differences between the bridge and autosampler grab sampling suggest that sediment transport was concentrated along the stream banks. This transport was comprised of particles enriched in organic matter as compared to those suspended within the water column. This provides some evidence that bank failure and erosion is a source of SSC. The data are not such as to be able to discount the possibility that sediment transport was also concentrated along the stream bed.

Table 15. Comparison of SSC and VSS at Long Avenue as collected with an autosampler deployed from the stream bank and depth-integrated sampling midstream from the bridge.

|           | <i>SSC (mg/L)</i> |                |      | <i>VSS (mg/L)</i> |                |          | <i>VSS/SSC</i>  |                |      |
|-----------|-------------------|----------------|------|-------------------|----------------|----------|-----------------|----------------|------|
| Date      | Auto<br>sampler   | Bridge<br>grab | Diff | Auto<br>sampler   | Bridge<br>grab | Diff     | Auto<br>sampler | Bridge<br>grab | Diff |
| 4/30/2008 | 6.2               | 7              | -12% | 1.7               | 1.7            | 0%       | 27%             | 24%            | 3%   |
| 4/10/2008 | 7.4               | 7.1            | 4%   | 1.7               | 1.4            | 19%      | 23%             | 20%            | 3%   |
| 4/23/2008 | 7.6               | 5.1            | 39%  | 2.8               | 1.8            | 43%      | 37%             | 35%            | 2%   |
| 6/4/2008  | 4.6               | 6              | -26% | 1.6               | 1.8            | -<br>12% | 35%             | 30%            | 5%   |
| 7/16/2008 | 21                | 13             | 47%  | 5                 | 2.25           | 76%      | 24%             | 17%            | 7%   |
| Mean      |                   |                | 10%  |                   |                | 25%      | 29%             | 25%            | 4%   |
| SD        |                   |                | 15%  |                   |                | 30%      | 6%              | 7%             | 2%   |

### ***Hydrodynamic modeling of the Crabtree Canal system***

Channel profile and bridges modeled using HEC RAS are illustrated in Figure 25. The mean velocity, the hydraulic depth, the shear stress and the total shear stress all decreased as the width of the floodplain increased relative to the top width of the main channel (Figures 26, 27, 28 and 29). The change in mean velocity, hydraulic depth, shear stress and total shear stress was greater between the smaller floodplain ratios such as 2, 3, and 5. There was a smaller change in the above-mentioned variables for larger floodplain ratios. There was a 13% decrease in shear stresses imposed upon the main channel between the trapezoidal channel and FPR 2 configuration. The greatest decrease in main channel shear stress occurred between FPR 3 and FPR 5 scenarios and was approximately 14%. The greatest decrease in total shear stress between the trapezoidal shape and FPR 20 configuration occurred in Reach 1 and was an 86% decrease. Values used to determine main channel average shear stress values presented in Figure 28 are biased by extremely high shear stress values at specific zones in the stream network. These high shear stress values occurred at points of inflection in bed profile or where the bed transitioned to a steeper slope (Figure 25). The high shear stress values were only encountered in the main channel. Shear stresses on the floodplain decreased with an increase in FPR values (dashed lines in Figure 28). The total shear stresses over the entire channel including the floodplain were not biased by high shear stress values caused by inflection points in the stream bed profile. This is due to the fact that the floodplain is relatively wide compared to the main channel therefore a weighted average of shear stresses over the entire length of the channel cross section is dominated by floodplain shear stresses (Figure 29).

There was a slight increase in mean velocity that occurs in the main channel of Reach 3, between current geometry and a FPR of 2. This increase is due to an increase in hydraulic radius between the current geometry and the modified FPR2 conditions.

HEC RAS separates the calculations for the main channel from calculations for the floodplain. The designated bank stations for the existing geometry provided a larger wetted perimeter which led to a smaller hydraulic radius than the FPR2 geometry. The increase in shear stress in the main channel of Reach 3 between current and FPR2 data is also due to an increase in hydraulic radius.

Critical shear stress for the channel was determined to be  $7.2 \text{ N/m}^2$  ( $0.15 \text{ lb/ft}^2$ ) based on the predominant soil type (Megget loam) encountered in proximity to the channel. In other words when shear stresses imposed upon the channel or floodplain are greater than this calculated critical shear stress, one could expect entrainment of bed or bank material. Critical shear stress was plotted on the graphs containing shear stress and total shear stress to illustrate those reaches and floodplain ratios that were vulnerable to erosion. In Figure 28, the main channel of Reach 1 and all floodplain areas are below the critical shear stress value. Lines representing the main channels of upstream reaches (Reaches 2 and 3) intersect the critical shear stress line between FPR 3 and FPR 5 data points. This suggests that that a floodplain configuration of at least FPR3 is needed to ensure shear stresses in the main channel do not exceed critical values.

Along with a general decrease in mean flow velocity, maximum flow depth and shear stress in the channel, an additional benefit to altering the floodplain configuration is additional storage volume. An FPR of 2 increases the flood storage up to  $230,000 \text{ m}^3$

(300,000 yd<sup>3</sup>). An FPR of 3 would produce a 79% increase in storage volume over a FPR 2 configuration. A FPR 5 configuration would produce a 220% increase; a FPR 7 would produce a 360% increase; a FPR 10 would produce a 563% increase and a FPR 20 would produce a 1420% increase in storage volume within the stream channel. Depending on the potential for flooding in the area at hand, one should consider a larger floodplain to accommodate larger volumes of flood waters.

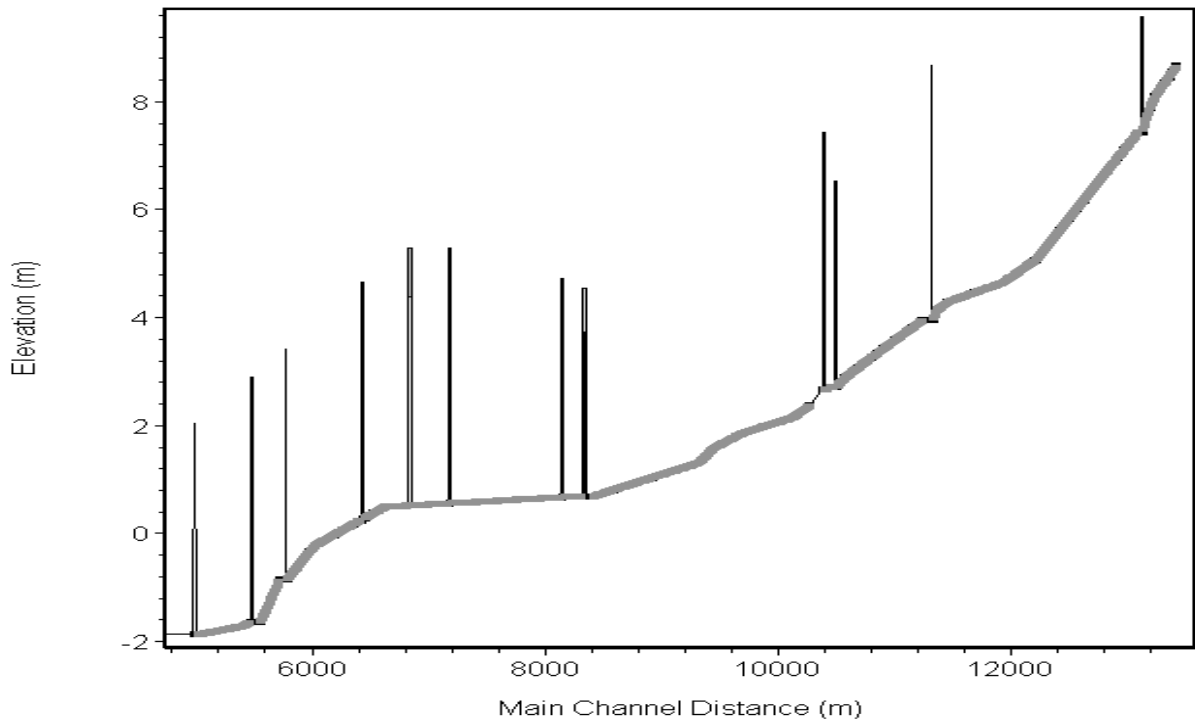


Figure 25. Streambed profile showing points of inflection and points where slope transitions to a steeper slope. Vertical lines represent bridges.

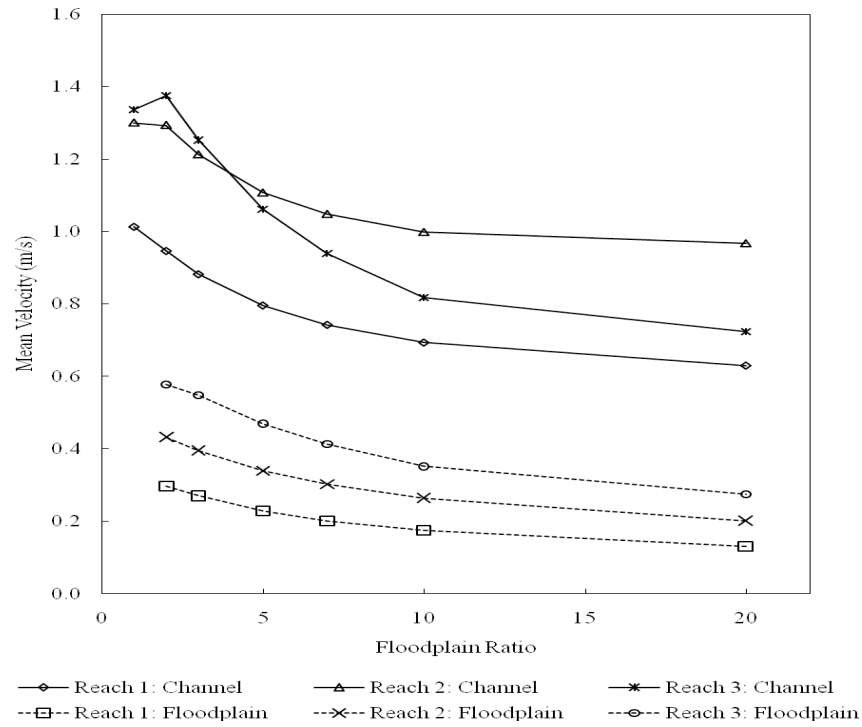


Figure 26. Mean velocity versus floodplain ratio for a simulated 2-year storm event. Solid lines represent the main channel and dashed lines represent floodplains.

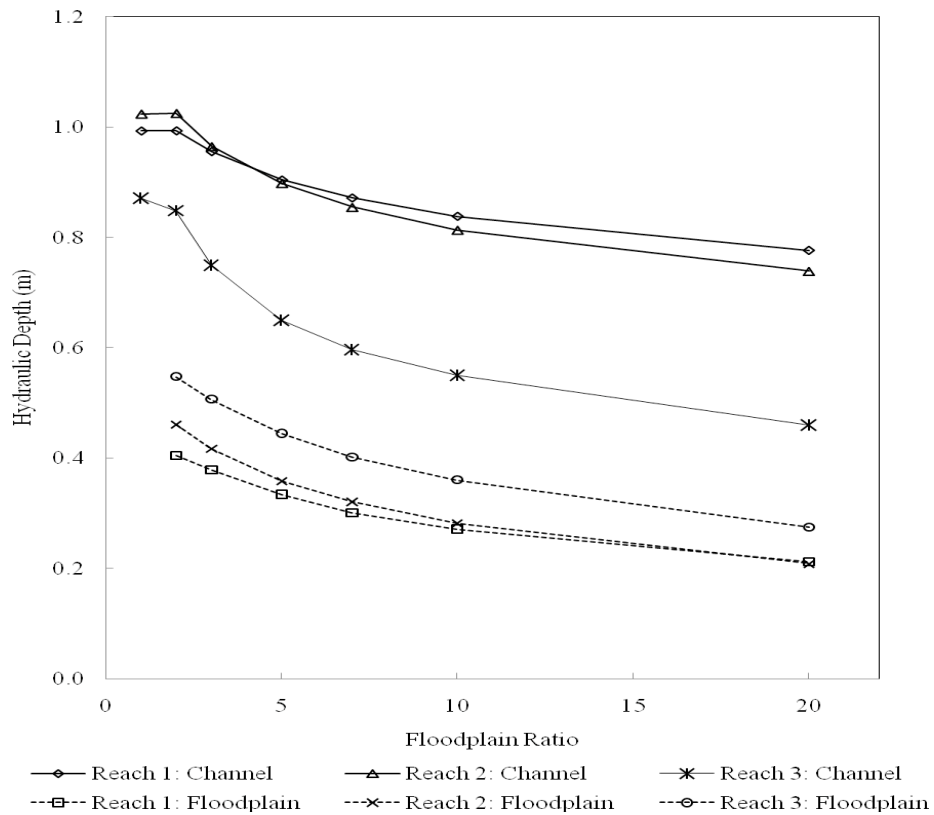


Figure 27. Hydraulic depth versus floodplain ratio for a simulated 2-year storm event.

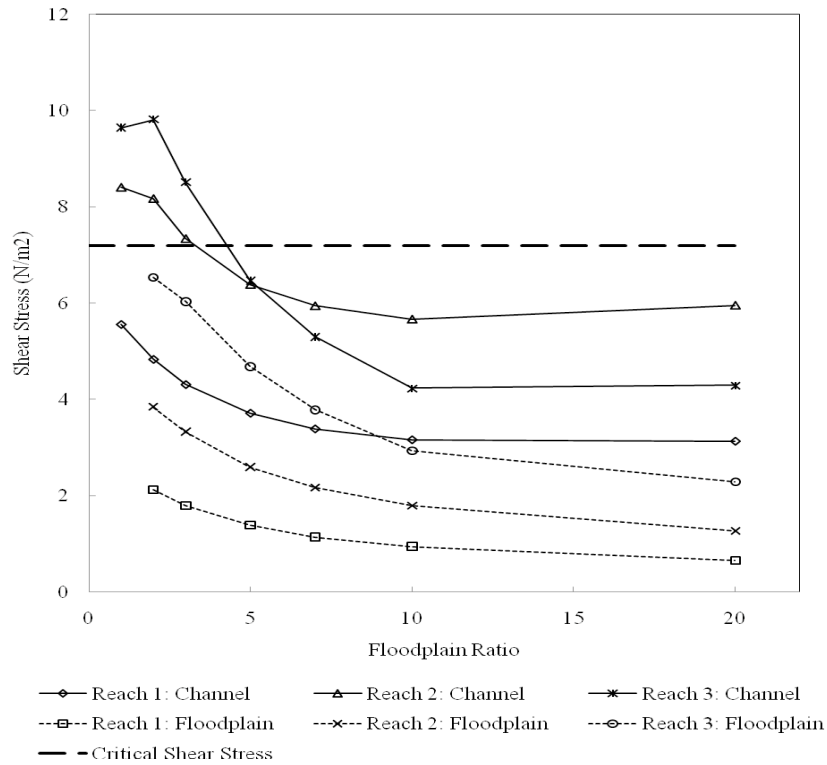


Figure 28. Shear stress on floodplain and main channel versus floodplain ratio for a simulated 2-year storm event.

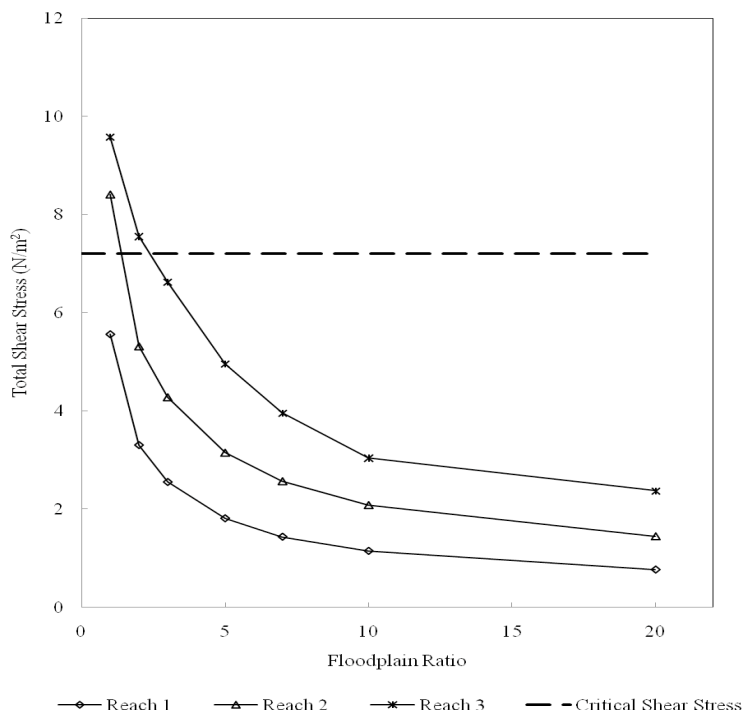


Figure 29. Total shear stress (channel and floodplain) versus floodplain ratio for a 2-year storm event.

## ***Conclusions***

The study determined the temporal and spatial distribution of suspended sediment loadings in the Crabtree watershed by measuring a handful of storms from January to August 2008. Three dry weather samplings were also made to determine ambient sediment loading in the watershed. The turbidity vs SSC regressions were robust at the Long Avenue sampling site and were used to infer SSC from continuous turbidity data being collected at 15 minutes intervals by the USGS in-situ sensor. Suspended sediment yields determined from 5 years of continuous turbidity suggests that the Crabtree watershed exhibits the characteristic high sediment yield of an unstable stream system based on a study by Simon and Klimetz (2008) on 24 Middle Atlantic Coastal Plain streams.

Crabtree Canal is on the 303(d) list for impairment due to deficits in dissolved oxygen. The poor correlation of BOD5 with either SSC or VSS suggests that most of the oxygen demand is associated with dissolved, rather than suspended, solids.

Wet weather events resulted in extreme elevations of turbidity and fecal coliforms with the highest concentrations found downstream of Hwy 501. The Stream at Wiegand Timber is notable for its consistently high wet weather turbidities and Mill Pond Stream for its contravention of fecal coliform water quality standards (WQS) during wet and dry weather.

At the watershed outlet (Long Avenue), the WQS for turbidity was contravened for a significant part of the project period based on the continuous record available from the USGS in-situ sensor. None of the biweekly grab sampling results contravened the WQS nor did any of the dry weather spatial survey observations. In contrast, wet weather contraventions were observed with more than half of the sites in violation during the last rain event sampled on 7/16/08 following a 1.8" accumulation. Nonetheless, this site is not 303(d) listed for turbidity as SC DHEC relies on monthly grab sampling. This failure to recognize sediments as a major pollutant obscures an important approach to managing the well-known chronic fecal coliform impairment.

Multiple lines of evidence suggest that the major source of sediments contributing to the elevated wet weather turbidities observed in the downstream segment of the Crabtree Canal are erosion from the stream banks in the main stem and a few of the tributaries, namely the Altman Branch. These lines of evidence include: (1) the response of turbidity to rainfall, (2) the higher SSC concentrations and %VSS near the stream banks, and (3) the constancy in composition of %VSS at Long Avenue and its enrichment in the headwaters of Crabtree. The similarity of SSC vs turbidity regressions amongst the data from Long Avenue (wet, dry, autosampler and bridge grab sample) also suggest a common source. The regressions upstream have somewhat different slopes and intercepts and are less well constrained, suggesting another and more variable source(s). The less well constrained relationship between SSC and turbidity upstream of Long Avenue confounds identification of which tributaries, besides the Stream at Weigand Timber and Altman Branch, are the largest sources of SSC.

Due to a lack of sampling sites in the main channel between West Road and Hwy 501, it is not possible to pinpoint the upstream location of streambank erosion. Several unsampled tributaries, such as Plum Creek, which discharge into Crabtree Canal at the Oak Street Bridge, could also be significant sources of sediment.

The hydrodynamic model that was developed was used to determine alternative floodplain configurations, and the impacts of these alternatives on hydrodynamics with the drainage system. It was shown that increases in floodplain ratio resulted in a significant decrease in total shear stress, average flow velocity, and hydraulic depth. The provision of greater floodplain was directly correlated to the decrease in the above-mentioned variables. The greatest decrease in these variables with floodplain width was in the upstream reaches, with less pronounced effects in the downstream reaches of the system. This study suggested that in the upstream reaches, a floodplain ratio greater than five was needed to ensure that a critical shear stress threshold was not exceeded.

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# Improved Early Detection Methods for Microcystin-Producing Cyanobacteria

## Basic Information

|                                 |  |
|---------------------------------|--|
| <b>Title:</b>                   | Improved Early Detection Methods for Microcystin-Producing Cyanobacteria |
| <b>Project Number:</b>          | 2008SC58B  |
| <b>Start Date:</b>              | 3/1/2008   |
| <b>End Date:</b>                | 2/28/2009  |
| <b>Funding Source:</b>          | 104B   |
| <b>Congressional District:</b>  | Third  |
| <b>Research Category:</b>       | Not Applicable   |
| <b>Focus Category:</b>          | Methods, Toxic Substances, Water Quality                                 |
| <b>Descriptors:</b>             | None   |
| <b>Principal Investigators:</b> | Alan R. Johnson, Yanru Yang  |

## Publication

# **Improved Early Detection Methods for Microcystin-Producing Cyanobacteria**

Final Report

Project Supported by the South Carolina Water Resources Center

Submitted  
10 August 2009

## **Principal Investigator:**

Alan R. Johnson, Associate Professor  
Department of Forestry & Natural Resources  
Clemson University  
Clemson, SC 29634  
Phone: 864-656-4390  
e-mail: [alanj@clemson.edu](mailto:alanj@clemson.edu)

## **Co-investigator.**

Yanru Yang, Assistant Professor  
Department of Environmental Engineering & Earth Sciences  
Clemson University  
Clemson, SC 29634  
Phone: 864-656-1448  
e-mail: [yyanru@clemson.edu](mailto:yyanru@clemson.edu)

## EXECUTIVE SUMMARY

The presence of cyanotoxins (toxins produced by cyanobacteria, also known as blue-green algae) in surface waters used for drinking water sources and recreation is receiving increasing attention around the world as a public health concern. Microcystins are a group of cyclic heptapeptides produced by various cyanobacteria, which upon ingestion exert marked toxic effects on the mammalian liver. Microcystins are the most commonly encountered class of cyanotoxin in drinking water, and have frequently been associated with acute poisoning of animals and occasionally humans, and pose a risk for chronic liver toxicity in humans. Microcystins impose considerable economic costs when the use of surface waters for drinking or recreation is impaired by the presence of microcystin-producing cyanobacteria. There is currently no Federal water standard for microcystins, but the World Health Organization has put forth a provisional “guideline value” of 1 µg/L (or 1 ppb) for microcystin-LR (the most common variant) in drinking water. The US Environmental Protection Agency has placed microcystin on the Contaminant Candidate List in consideration of developing a drinking water standard.

Environmental managers can select from a wide array of types of measurements to design a monitoring protocol for cyanobacteria and associated toxins. Each monitoring procedure has associated benefits and costs, and each type of measurement carries some potential for false positive or false negatives. There is a need to develop a decision support framework that would allow a systematic assessment of the trade-offs involved in any particular monitoring and management strategy.

This project focused on the development of molecular genetic methods for detecting genes associated with the synthesis of microcystins, and comparing these methods with the widely used ELISA assay for microcystin. The ELISA assay was found to be relatively easy, reproducible, and quite sensitive. The PCR assay was fairly easy once developed, but the detection limit was rather variable, and the assay was not as sensitive expected. The rather variable and sometimes poor detection limit means that the PCR assay could yield a substantial rate of false negative results if microcystin-producing cyanobacteria are present at relatively low concentration. We attempted to implement a quantitative PCR method, but were never able to get reliable results with cyanobacterial samples.

A generic decision framework was constructed which will be presented at the 2009 Society of Environmental Toxicology and Chemistry annual meeting in New Orleans. Although the conclusions are highly dependent on site-specific conditions and on the costs associated with various possible outcomes, it is clear that in situations where bloom dynamics are uncertain (e.g., where there is not a substantial history of past blooms), and costs associated with mistaken action are high, it may be rational to not take management actions until the bloom is unmistakably underway. At that point, the only feasible management might be measures to prevent exposure. Alternatively, in ecosystems with a documented history of blooms, early detection by routine monitoring might make early intervention by chemical or other bloom control techniques more desirable. Further development of this decision framework is planned, contingent upon securing additional funding to support this avenue of research.

## INTRODUCTION AND BACKGROUND

The presence of toxins produced by cyanobacteria, (also known as blue-green algae) in surface waters used for drinking water sources and recreation is receiving increasing attention around the world as a public health concern (Chorus and Bartram 1999, Falconer 2005). Microcystins are toxins produced by various cyanobacteria, which upon ingestion exert harmful effects on the mammalian liver. They have frequently been associated with acute poisoning of animals and occasionally humans, and pose a risk for chronic liver toxicity in humans (Carmichael and Falconer 1993, Hitzfield et al. 2000). Microcystins impose considerable economic costs when the use of surface waters for drinking or recreation is impaired by the presence of microcystin-producing cyanobacteria. The World Health Organization has established a guideline value of 1 µg/L (or 1 ppb, as microcystin-LR, the most common variant) in drinking water.

Environmental managers can select from a wide array of types of measurements to design a monitoring protocol for cyanobacteria and associated toxins. These range from traditional microscopic, chemical and limnological data, to molecular genetic techniques which have recently been developed or are anticipated to be available in the near future. Each monitoring procedure has associated benefits and costs, and each type of measurement carries some potential for false positive or false negatives. Selection of an appropriate monitoring protocol requires a quantitative assessment of the value of information and the risks associated with delay to obtain more detailed information versus the risks associated with possible management or remediation actions. Increasing attention has been directed toward tiered monitoring protocols that seek to maximize benefits and minimize the costs. There is a need to develop a decision support framework that would allow a systematic assessment of the trade-offs involved in any particular monitoring and management strategy.

## METHODOLOGY

This project would allowed us to develop the capability to use molecular genetic techniques, based on polymerase chain reaction (PCR) and quantitative (real-time) PCR (q-PCR), to detect microcystin-producing cyanobacteria in natural waters in South Carolina. We compared the sensitivity (detection-level) of these molecular techniques with the widely used enzyme-linked immunosorbent assay (ELISA) method which directly measures microcystin levels. This assessment was done both in relatively “pure” cultures, and in samples containing a rich algal and bacterial assemblage typical of eutrophic surface waters, in order to evaluate possible interferences from non-target DNA or other substances that would be commonly encountered in a monitoring program.

**Algal Culture.** The cyanobacterial strain used to establish a laboratory culture was ordered from the University of Texas Culture Collection of Algae (UTEX, [www.utex.org](http://www.utex.org)). We worked with the LB 2385 strain of *Microcystis aeruginosa* Kütz em Elenkin, which was isolated in 1954 from Little Rideau Lake in Ontario, Canada, and is reported by the UTEX database to be a producer of microcystin.

**Microcystin Measurement.** Enzyme-linked immunosorbent assay (ELISA) methods for detection of microcystins have been developed. These methods display high sensitivity for the specific compound used to raise antibodies, but varying degrees of cross-reactivity raise the possibility of false negatives when used to detect other, closely related toxins. For instance, the one of the monoclonal antibodies raised by Nagata et al. (1995) against microcystin-LR showed high cross-reactivity with some other isoforms (e.g., microcystin-RR 106%) but lower cross-reactivity with other isoforms (e.g., microcystin-YR 44 %, microcystin-LA 26%). The antibody also reacts with nontoxic monomethyl ester of microcystin-LR, giving a false positive from a toxicological viewpoint.

We used a commercially available ELISA test kit from Abraxis to measure microcystins. The test is an indirect competitive ELISA that allows the quantitative, congener-independent detection of microcystins and nodularins. It is based on the recognition of microcystins, nodularins and their congeners by specific antibodies.

### ***Molecular Genetic Measurements.***

Quantitative (real-time) PCR. To attempt quantitative measurement of microcystin-producing cyanobacteria, samples were subjected to real-time PCR analysis to quantify the copy numbers of microcystin synthetase gene, *mcyE* gene. The results will then be used to infer the abundance of cells carrying these target genes in the original samples.

DNA was extracted as described in Coyne et al. (2001). Real-time PCR will be performed in a spectrofluorimetric thermal cycler (ABI Prism 7900 Sequence Detection System; Applied Biosystems). Each reaction contains TaqMan Universal PCR Master Mix (including DNA polymerase, deoxynucleoside triphosphates, and MgCl<sub>2</sub>) (Applied Biosystems); forward primer, reverse primer, and TaqMan probe; and DNA template from each 10-fold-diluted sample. The probe contains 6-carboxy-fluorescein (FAM) as a reporter fluorochrome on the 5' end, and *N,N,N',N'*-tetramethyl-6-carboxy-rhodamine (TAMRA) as quencher on the 3' end. Assays were performed with a four-step thermo-profile: denaturing of DNA, annealing of primers under stringent conditions at an assay-specific temperature, elongation, and fluorescence data acquisition during an additional temperature step. A calibration curve (log DNA concentration versus an arbitrarily set cycle threshold value C<sub>T</sub>) was obtained by using serial dilutions of DNA of known concentration. The C<sub>T</sub> values obtained for each sample were compared with the standard curve to determine the initial DNA concentration.

***Evaluation of Detection Method Sensitivity.*** The actively growing cultures of microcystin-producing *Microcystis aeruginosa* were grown to reach high density (on the order of 10<sup>6</sup> cells/L). These stock cultures will be diluted to produce cell densities spanning several orders of magnitude, and each of the diluted samples will be analyzed by all three detection methods (microcystin ELISA, PCR and quantitative PCR) to determine the detection limit of each method. Two sorts of dilutions were made. First, the stock culture will be diluted with growth medium. This will determine the detection limit in a relatively pure (although not axenic) culture. Secondly, the stock culture will be diluted with unfiltered surface water from a eutrophic system which has a rich bacterial and algal community, but which is not suspected to harbor microcystin-producing cyanobacteria. This allowed us to estimate the detection limit of

the methods in realistic conditions where DNA, mRNA and peptides from a diverse assemblage of microbes are present, which might act to interfere with the test, creating false positives or false negatives.

## RESULTS AND CONCLUSIONS

The Abraxis ELISA assay was found to be relatively easy, reproducible, and quite sensitive. The manufacturer reports a detection limit of 0.10 ppb as microcystin-LR, and we usually achieved a similar detection limit based on dilutions of our microcystin standard solution.

The PCR assay took some work to perfect (trying different primers and temperature conditions), but once the experimental details were worked out, it was fairly easy and reliable. However, the detection limit was rather variable, and often the assay was not as sensitive as would be expected based on the literature. Also, occasionally, a gel would be uninterpretable, due to some DNA contamination or some other unexplained problem in the procedure. An interpretable result was always achieved by re-running the sample, but this introduced a delay that would be undesirable in a routine monitoring program. The rather variable and sometimes poor detection limit means that the PCR assay could yield a substantial rate of false negative results if microcystin-producing cyanobacteria are present at relatively low concentration.

We attempted the quantitative PCR method. Although the assay yielded a good calibration curve with a standard DNA sample, we were never able to get reliable results with cyanobacterial samples. Thus, we are unable to evaluate detection limits or error rates associated with this procedure.

It should be noted that, soon after this project was started, Dr. Yang (the co-investigator) left Clemson University to take a position elsewhere. This left Vanessa Molina, the graduate student working on the project, in the awkward position of carrying on after the collaborator with laboratory expertise in molecular genetic techniques was no longer around. This did delay our work, but in the end Ms. Molina was able make substantial progress with a combination of e-mail consultations with Dr. Yang, and assistance from a variety of knowledgeable faculty and graduate students at Clemson University. It could be argued that some of our problems with implementing the molecular techniques were a result of the lack of Dr. Yang's expertise. However, the difficulties we faced are not substantially different than other laboratories might face in implementing new procedures. Laboratories with extensive experience in the molecular techniques in question might be able to attain better results, but ours are probably typical for labs as they adopt new procedures.

Early detection of microcystin-producing cyanobacteria is essential if action is to be taken to manage the associated risks to humans or domestic animals via reducing exposure (limiting access, treatment of drinking water, etc.) or control of bloom dynamics (mixing of the water column, algaecide treatment, etc.). A generic decision framework was constructed which will be presented at the 2009 Society of Environmental Toxicology and Chemistry annual meeting in New Orleans. Although the conclusions are highly dependent on site-specific conditions and on the costs associated with various possible outcomes, it is clear that in situations where bloom dynamics are uncertain (e.g., where there is not a substantial history of past blooms), and costs

associated with mistaken action are high, it may be rational to not take management actions until the bloom is unmistakably underway. At that point, the only feasible management might be measures to prevent exposure. Alternatively, in ecosystems with a documented history of blooms, early detection by routine monitoring might make early intervention by chemical or other bloom control techniques more desirable.

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# **Information Transfer Program Introduction**

None.

# **USGS Summer Intern Program**

None.

| <b>Student Support</b> |                               |                               |                             |                            |              |
|------------------------|-------------------------------|-------------------------------|-----------------------------|----------------------------|--------------|
| <b>Category</b>        | <b>Section 104 Base Grant</b> | <b>Section 104 NCGP Award</b> | <b>NIWR-USGS Internship</b> | <b>Supplemental Awards</b> | <b>Total</b> |
| <b>Undergraduate</b>   | 0                             | 0                             | 0                           | 0                          | 0            |
| <b>Masters</b>         | 5                             | 0                             | 0                           | 0                          | 5            |
| <b>Ph.D.</b>           | 3                             | 0                             | 0                           | 0                          | 3            |
| <b>Post-Doc.</b>       | 0                             | 0                             | 0                           | 0                          | 0            |
| <b>Total</b>           | 8                             | 0                             | 0                           | 0                          | 8            |

## Notable Awards and Achievements

**University of Delaware** Invited to UD and provided a workshop for faculty and administrators on urban growth modeling and potential affects of urban growth on receiving waters. **SUNY Albany** Invited to SUNY and provided a workshop on sustainable growth, local policy and environmental protection for small municipalities. **SC Sea Grant** Invited to three South Carolina coastal communities to provide information on coastal growth, potential environmental impacts from that growth and potential policy implications at the local, state and federal levels. **Mott Foundation** Met with members of the Mott Foundation in Ann Arbor, Michigan to determine possible avenues of collaboration concerning aging dams in the Southeast and potential chemical contamination in impoundments. **U.S. Forest Service** Invited to present information to a national USFS short course concerning urbanization and impacts to forests and other natural resources. **Clemson University Water Forum** Co-hosted an educational forum for administrators, faculty and students in order to build a more cohesive network of water research on campus. **Leadership South Carolina** Invited to address group on a broad range of natural resource and water issues facing South Carolina in the upcoming decades. **Catawba River Basin Commission** Invited to address the Commission on work of the SCWRC and how the Center might assist the Commission as it works toward settling issues between SC and NC. **State Mapping Advisory Committee** Invited to make a presentation at the annual meeting regarding using GIS and computer mapping technologies toward solving problems related to natural resource and water management. **Assessing suspended sediment transport potential and supply in an urbanizing coastal plains stream.** A one dimensional hydrodynamic model has been developed, tested and delivered to local stormwater management agencies for additional testing and feedback. The model served to provide some basis for the restoration of a reach within the Crabtree Canal system that conveys stormwater through the City of Conway, SC. Work on approximately 2400 linear feet of a degraded section of Crabtree Canal was initiated based on research supported through this grant. A The results from work supported through this grant are being prepared for submission for publication in peer-reviewed journals.

The SCWRC hosted a summer intern in 2008 through a co-sponsorship with the Clemson Department of Civil Engineering. The intern worked primarily on data gathering for planned projects with the U.S. Army Corps of Engineers on Lake Hartwell and the Pickens County Water Supply Plan for the Pickens County Water Authority.

## Publications from Prior Years

1. 1996SC101B ("Assessment of the Effect of Bioturbation on Advective Contaminant Exchange at the Sediment Stream Interface") - Water Resources Research Institute Reports - Work, Paul A., Paul Moore, John McEnery and D.D. Reible. 1999. Assessment of the Effect of Bitrubation on Advective Contaminant Exchange at the Sediment Stream Interface. South Carolina Water Resource Center, Clemson University, Clemson, SC 180 pages.
2. 1996SC101B ("Assessment of the Effect of Bioturbation on Advective Contaminant Exchange at the Sediment Stream Interface") - Dissertations - Moore, Paul Roland. 1999. Bioturbation and Pore Water Exchange in a Laboratory Flume. MS Dissertation, Civil Engineering, Clemson University, Clemson, SC, 165 pages.
3. 1996SC101B ("Assessment of Effect of Bioturbation on Advective Contaminant Exchange at the Sediment Stream Interface") - Dissertations - McEnery, John Anthony. 2000. Interstitial Pore Water Flux through Streambeds of Varying Composition, Ph.D. Dissertation. Civil Engineering, Clemson University, Clemson, SC, 172 pages.
4. 2000SC1B ("Assessment of Conditions and Public Attitudes Concerning Marine Sanitation of the Lakes Encompassed by the Savannah River Watershed Region: Policy Projections for the Future") - Water Resources Research Institute Reports - Backman, Kenneth F. and Sheila J. Backman. 2000. Assessment of Conditions and Public Attitudes Concerning Marine Sanitation of the Lakes Encompassed by the Savannah River Watershed Region. South Carolina Water Resources Center, Clemson University, Clemson, SC, 35 pages
5. 2000SC1B ("Assessment of Conditions and Public Attitudes Concerning Marine Sanitation of the Lakes Encompassed by the Savannah River Watershed Region: Policy Projections for the Future ") - Conference Proceedings - Backman, Sheila J. and Kenneth F. Backman. 2001. Perceptions of Water Quality in the Five Lake Savannah Watershed Region. In College of Health, Education and Human Development Faculty Research Forum, Clemson University, Clemson, SC, p. 3.
6. 2000SC1B ("Assessment of Conditions and Public Attitudes Concerning Marine Sanitation of the Lakes Encompassed by the Savannah River Watershed Region: Policy Projections for the Future") - Conference Proceedings - Davis, Jason and Kenneth F. Backman. 2001. Boaters and Marine Operators Perceptions of Water Quality in the Five Lake Savannah Watershed Region. In Southeastern Recreation Research Conference, Asheville, NC, February 21-23.
7. 2000SC1B ("Assessment of Conditions and Public Attitudes Concerning Marine Sanitation of the Lakes Encompassed by the Savannah River Watershed Region: Policy Projections for the Future") - Conference Proceedings - Walker, Joseph and Kenneth F. Backman. 2001. Exploring the Effect of Trip Distance on Boaters Perception of Water Quality. In Southeastern Recreation Research Conference, Asheville, NC, February 21-23.
8. 2000SC44B ("Initiating Effective Algae Reduction on Lake Greenwood, South Carolina") - Conference Proceedings - Blacklocke, Sean. 1999. Regulating Animal Agriculture in America: Who Benefits? In 80th Annual Conference of the American Farm Bureau Federation, Albuquerque, NM. p. 9.
9. 2000SC44B ("Initiating Effective Algae Reduction on Lake Greenwood, South Carolina") - Conference Proceedings - Blacklocke, Sean. 1999. An Inquiry into the Rationale for Prioritizing South Carolinas Animal Feeding Operations for Water Pollution Regulation. In 1st Annual South Carolina Water and Environmental Symposium, University of South Carolina, Columbia, SC.
10. 2000SC3B ("Restablishment of an Estuarine Marsh and Waterway after Causeway Removal") - Water Resources Research Institute Reports - Curran, Mary Carla, Randall Cross and Earl J. Hayter. 2001. Reestablishment of an Estuarine Marsh and Waterway after Causeway Removal. South Carolina Water Resources Center. Clemson University, Clemson, South Carolina, 11 pages.
11. 2001SC3781B ("Reservoir Shoreline Erosion and Sediment Deposition with Cohesive Sediments") - Water Resources Research Institute Reports - Elci, Sebnem and Paul A. Work. 2002. Prediction of

- Shoreline Erosion and Sedimentation in Hartwell Lake, SC/GA, Georgia Tech Regional Engineering Program Civil and Environmental Engineering, Report No. GTREP-CEE/2002-1, South Carolina Water Resources Center, Clemson University, Clemson, South Carolina, 97 pages.
12. 2001SC3761B ("Using Spatial Techniques to Assess the Contribution of Animal Agriculture on Watershed Impairment for the Saluda River Watershed in South Carolina") - Water Resources Research Institute Reports - Lu, Kang S. and Jeffery S. Allen. 2001. Animal Agriculture and Watershed Impairment in South Carolina. South Carolina Water Resources Center, Clemson University, Clemson, SC, 69 pages.
  13. 2002SC1B ("Using Remote Sensing and GIS Technology to Assess the Relationship of Land Cover to Watershed Impairment for the Saluda River Basin South Carolina") - Conference Proceedings - Lu, Kang S. and Jeffery S. Allen. 2003. Animal Agriculture and Watershed Impairment in South Carolina: A GIS-based spatial assessment. In Ninth International Symposium on Animal, Agriculture and Food Processing Waste (ISAAFPW 2003), Durham, NC.
  14. 2002SC1B ("Using Remote Sensing and GIS Technology to Assess the Relationship of Land Cover to Watershed Impairment for the Saluda River Basin South Carolina") - Other Publications - Allen, Jeffery S. and Kang S. Lu. 2002 Animal Agriculture and Watershed Impairment in South Carolina. Report submitted to PSA Agrisystems Productivity and Profitability Competitive Grants Program.
  15. 2002SC1B ("Using Remote Sensing and GIS Technology to Assess the Relationship of Land Cover to Watershed Impairment for the Saluda River Basin South Carolina") - Other Publications - Allen, Jeffery S. and Kang S. Lu. 2002. Modeling and Predicting Future Urban Growth in the Charleston, South Carolina Area. Special issue of Conservation Ecology, {on-line} URL: <http://www.consecol.org/vol8/iss2/art2>.
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